Chapter 16
Loess Records

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Abstract Loess is aeolian sediment, dominated by silt-sized particles, that is identifiable in the field as a distinct sedimentary body. It covers a significant portion of the land surface of the Earth and as such constitutes one of the most important archives of long-term dust deposition. Large tracts of loess cover Europe, Asia, South America, and North America, and smaller loess bodies are found covering parts of Africa, the Middle East, New Zealand, and Australia. Loess thickness, particle size, and carbonate content decrease downwind from sources, trends that are powerful tools for reconstructing paleowinds. Many loess sections consist of

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relatively thick deposits of mostly unaltered sediment with intercalated paleosols. Paleosols represent periods of landscape stability when loess deposition ceased or at least slowed significantly. Studies from several continents show that loess in most regions was deposited during glacial periods and paleosols formed during interglacial and interstadial periods.

Keywords Loess • Glacial • Interglacial • Silt • Paleosol • Deposition • Mineralogy • Geomorphology • Sediment • Stratigraphy • Geochronology • Dispersal • Paleoclimate • Records • Archive • Aeolian • Quaternary

16.1 Introduction

Loess is aeolian (windblown) sediment and is one of the most extensive surficial deposits on the surface of the Earth. Loess has come to be regarded as one of the most important archives of long-term dust deposition and Quaternary climate change. Combined with intercalated paleosols (buried soils), loess provides one of the most complete terrestrial records of glacial–interglacial cycles. Loess is distinctive in that it is one of the few Quaternary sediments that provides a direct record of atmospheric circulation. Thus, given favorable circumstances, loess can be used to reconstruct synoptic-scale paleoclimatology over millennial timescales. Finally, loess is unusual in that it can be dated directly using methods, such as luminescence geochronology, that require only the sediment itself. Thus, the combination of loess deposits, fossil remains, and intercalated paleosols provides a highly valued source of information of Quaternary paleoclimate.

16.2 Definition of Loess

Loess can be defined as sediment, dominated by silt-sized particles, that has been entrained, transported, and deposited by the wind. It differs from other dust archives (deep-sea cores, ice cores; see Muhs (2013a) for a review) in that it is found on land and is identifiable in the field as a distinct sedimentary body (Figs. 16.1 and 16.2). Loess occupies an intermediate position in a continuum of aeolian sediments, with an average particle size that is smaller than windblown sand (2–0.05 mm) but coarser than long-range-transported (LRT) dust (typically <10 μm). Commonly, loess contains 60–90 % silt-sized (50–2 μm diameter) particles, with smaller amounts of sand (>50 μm) and clay (<2 μm). Some loess deposits are more sand rich and others are more clay rich, but all have a dominance of silt-sized particles. Loess is also much more poorly sorted than aeolian sand or LRT dust. The wide range of mean particle size and relatively poor sorting can be the result of (a) multiple sources, (b) clay-sized particles being transported as

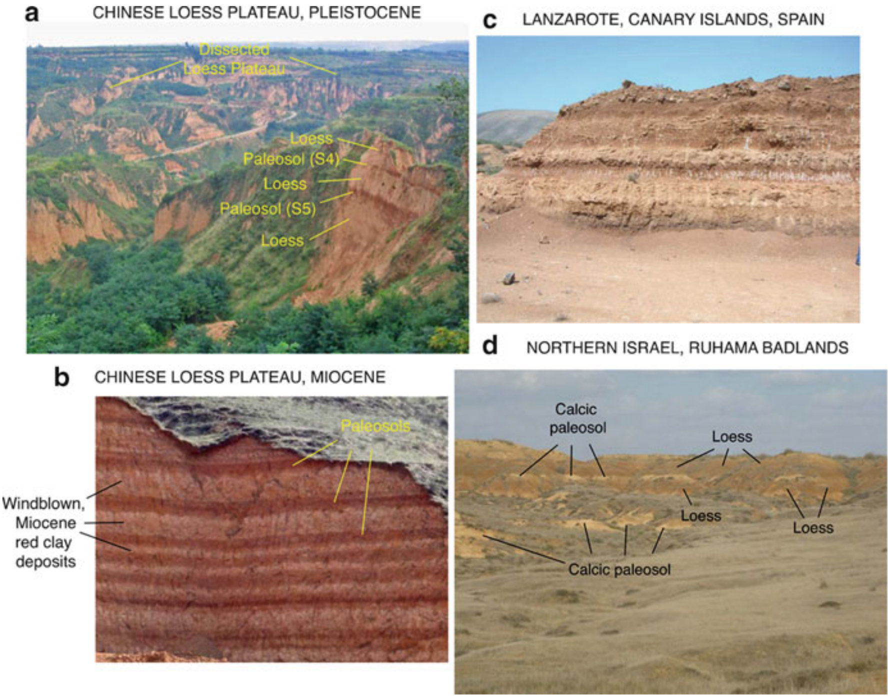


Fig. 16.1 Gallery of loess exposures from around the world, 1: (**a**) dissected loess plateau landscape and Pleistocene loess exposed at Luochuan, Chinese Loess Plateau – "L" prefix indicates loess units, and "S" prefix indicates paleosols; (**b**) Miocene Red Clay on the Chinese Loess Plateau (section is ∼10 m thick, light bands are aeolian clay, and dark bands are paleosols) (photo by Youbin Sun); (**c**) loess-like (fluvially and colluvially reworked) sediment exposed near Guatiza, Lanzarote, Canary Islands, Spain (see von Suchodoletz et al. (2009) for detailed study); (**d**) Pleistocene loess and paleosols exposed in the Ruhama badlands area, northern Negev Desert of Israel

silt-sized aggregates (see discussion by S. Cattle below), (c) loess bodies extending considerable distances from their sources, and/or (d) varying wind strengths over time.

Loess thickness is highly variable. It can range from a few centimeters to several hundred meters in thickness. Indeed, variability of loess thickness is one of its advantages as a paleoclimate indicator, as we discuss below. Loess deposits are commonly draped over preexisting landforms as a mantle, with thickest accumulations in protected, low-lying areas or broad, flat, stable upland divides and thinnest accumulations occurring on narrow, rounded hillcrests. Loess deposits can be intercalated with other sorts of sediments, such as tephras, where there is active volcanism, as is the case in Iceland, South America, Alaska, and New Zealand. Commonly, multiple loess units are apparent in outcrop, separated by paleosols that mark periods of cessation of loess deposition or at least periods when loess sedimentation rates were greatly diminished.

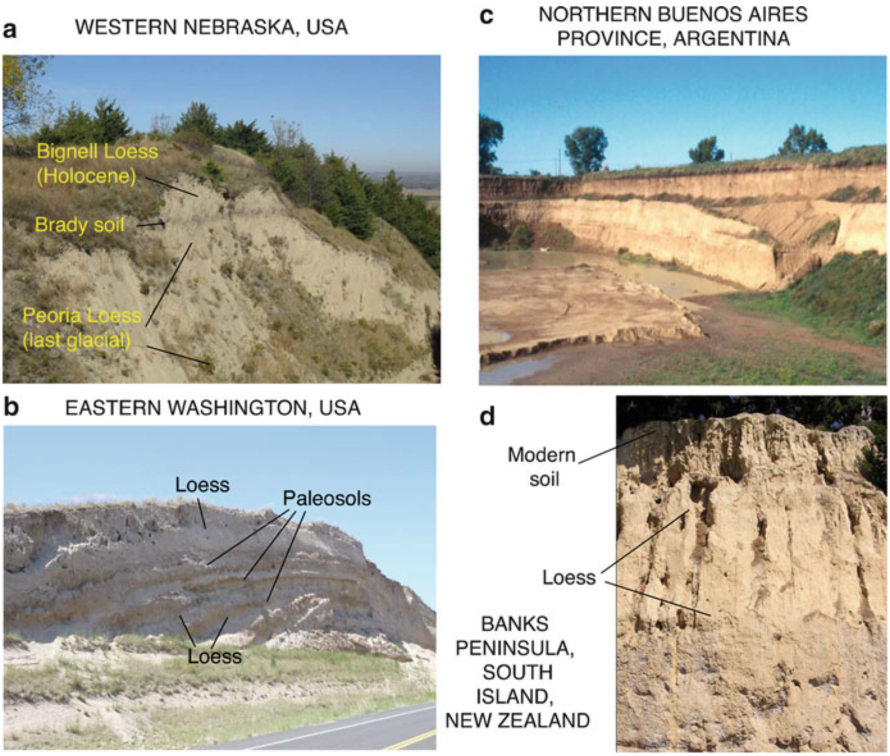


Fig. 16.2 Gallery of loess exposures from around the world, 2: (**a**) non-glacial Holocene and Pleistocene loess at Bignell Hill, Nebraska, Great Plains of the USA (see Muhs et al. (2008) for detailed study); (**b**) Pleistocene loess and paleosols exposed in a roadcut in the Palouse loess country of eastern Washington, USA; (**c**) Pleistocene loess exposed in the Pampas region, northern Buenos Aires province, Argentina; (**d**) Pleistocene loess and modern soil exposed on the Banks Peninsula, South Island, New Zealand

16.3 Mineralogy and Geochemistry of Loess

Loess typically has a mineralogy that reflects a mixture of sources, but most loess is derived from upper crustal source rocks. Exceptions to this include loesses derived from mafic volcanic rocks in Iceland, parts of New Zealand, and parts of South America. Elsewhere, on most continents, loess deposits typically include quartz, plagioclase, K-feldspar, mica, calcite (sometimes with dolomite), and phyllosilicate clay minerals (smectite, chlorite, mica, and kaolinite). Heavy minerals are usually present but commonly are found only 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 %, reflecting a dominance of quartz. Lower concentrations of quartz, feldspars, and micas in glaciogenic loess from North

America are due to higher amounts of carbonate minerals (dolomite and calcite), derived from dolostones and limestones that were traversed by the Laurentide ice sheet (mid-continent) and valley glaciers (Alaska).

16.4 Genesis of Loess Deposits

Although few (if any) modern investigators doubt the aeolian origin of loess, there is still considerable debate about the specific processes whereby silt particles are generated before they are entrained by the wind. The issue is whether silt particles in loess can be produced only by glacial grinding or if they can be produced in sufficient quantities by other processes. Thus, the debate has been between advocates of "glacial loess" versus those of "desert loess" (see reviews in Pye 1995; Tsoar and Pye 1987; Smalley 1995; Livingstone and Warren 1996; Wright 2001a; Muhs and Bettis 2003; Muhs 2007, 2013b).

The "glacial loess model" proposes that silt-sized particles are produced mostly by glacial grinding of bedrock surfaces, deposition as till, reworking by fluvial processes as outwash, and finally entrainment, transportation, and deposition by wind. Glaciers are efficient producers of silt, and the close geographic association of loess with glacial terrain supports this model.

"Desert" loess is a term that has been applied to aeolian silt generated in and/or derived from arid or semiarid regions that were not glaciated. Silt-sized particles found in what has been called desert loess may be derived from a variety of non-glacial processes. These processes include frost shattering, chemical weathering, salt weathering, fluvial comminution, and aeolian abrasion and ballistic impacts (Wright 2001b). Examples of desert loess formed by these processes are given below.

An often overlooked source of silt is particle inheritance from sedimentary rocks, such as siltstones and shales. Silt is abundant in the geologic record. In fact, Blatt (1987) estimates that fully half of the detrital quartz in the world's sedimentary rocks is comprised of silt-sized particles. Furthermore, silt-sized volcanic ash particles form the major or at least a significant source for many of the loess deposits in South America, Iceland, Alaska, and New Zealand. We stress that the multiple pathways of loess particle origins are not mutually exclusive. It is likely that loess in many regions has origins from both glacial and non-glacial processes, as well as some silt-particle inheritance.

16.5 Loess Stratigraphy

Paleosols are common in loess sections (Figs. 16.1 and 16.2). In most regions, glacial periods are dominantly times of loess deposition, whereas interglacial and interstadial periods are dominantly times of soil formation. Thus, this alternation of glacial times of loess deposition and interglacial times of soil formation has been correlated with the deep-sea oxygen isotope record of glacial–interglacial cycles. In general, this model has validity, but when loess records are examined in more detail, the stratigraphy is rarely simple. Perhaps a more realistic way to view the system is to consider loess sedimentation and soil formation as 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). In contrast, when loess sedimentation rates are low, soil-forming processes extend deeper into previously deposited loess. Thus, whereas in deep-sea or lacustrine sediments, a case can be made for more or less continuous sedimentation, loess–paleosol sequences are more complex systems, and distinguishing between sediment and soil is not always an easy task. Examples of loess–paleosol sequences are provided below.

16.6 Loess Geochronology

Precisely because sedimentation is *not* continuous in loess–paleosol sequences, numerical dating is essential in loess stratigraphy. A particularly illuminating example of this is the study by Stevens et al. (2007), where an extensive suite of luminescence ages demonstrates that many loess sequences in China have been affected by nonconstant sedimentation rates, diagenesis, bioturbation, and erosion. Muhs et al. (2003), using a combination of radiocarbon ages, tephrochronology, and inventory ^{10}Be methods, show that loess sequences in Alaska contain numerous unconformities. Today, the most commonly used methods in dating loess are paleomagnetism, luminescence geochronology, radiocarbon dating, and magnetic susceptibility (see review in Muhs (2013b)).

16.7 Paleoclimatic and Paleoenvironmental Interpretation of Loess Deposits

Much valuable paleoenvironmental information can be obtained from loess–paleosol sequences, particularly because loess covers large areas of most continents (Figs. 16.3, 16.4, 16.5, and 16.6). Loess properties can change over a landscape, and these variations can yield important clues about the paleowinds that deposited the loess. Thickness of loess, particle size, and carbonate content, in general, decrease away from sources (Liu 1985; Porter 2001; Bettis et al. 2003; Muhs and Bettis 2003; Muhs et al. 2004, 2008, Muhs 2013b). Reduction in sediment load downwind from a source is inferred from decreases in loess thickness. Paleowinds can also be inferred from the decrease in mean particle size away from a source, reflecting a winnowing of the coarse load. With decreases in loess deposition rate away from a source, there is often syndepositional leaching, reflected in a decrease in carbonate content. Thus, if a hypothesized 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.

In contrast to unaltered loess itself, loess-hosted paleosols frequently yield valuable information about interglacial or interstadial periods. Measurement of magnetic susceptibility and other mineral magnetic properties has been one of the most common approaches to interpreting paleoclimate from loess-hosted paleosols (Verosub et al. 1993; Maher et al. 1994; Porter 2001; Porter et al. 2001; Singer and Verosub 2007). Unfortunately, one problem that arises 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. Porter et al. (2001) show that both of these factors are spatially variable but highly correlated with one another (and climate) across the Chinese Loess Plateau. Another approach is to examine the degree of chemical weathering in loess-derived paleosols, as this reflects past climate and vegetation (Muhs 2007).

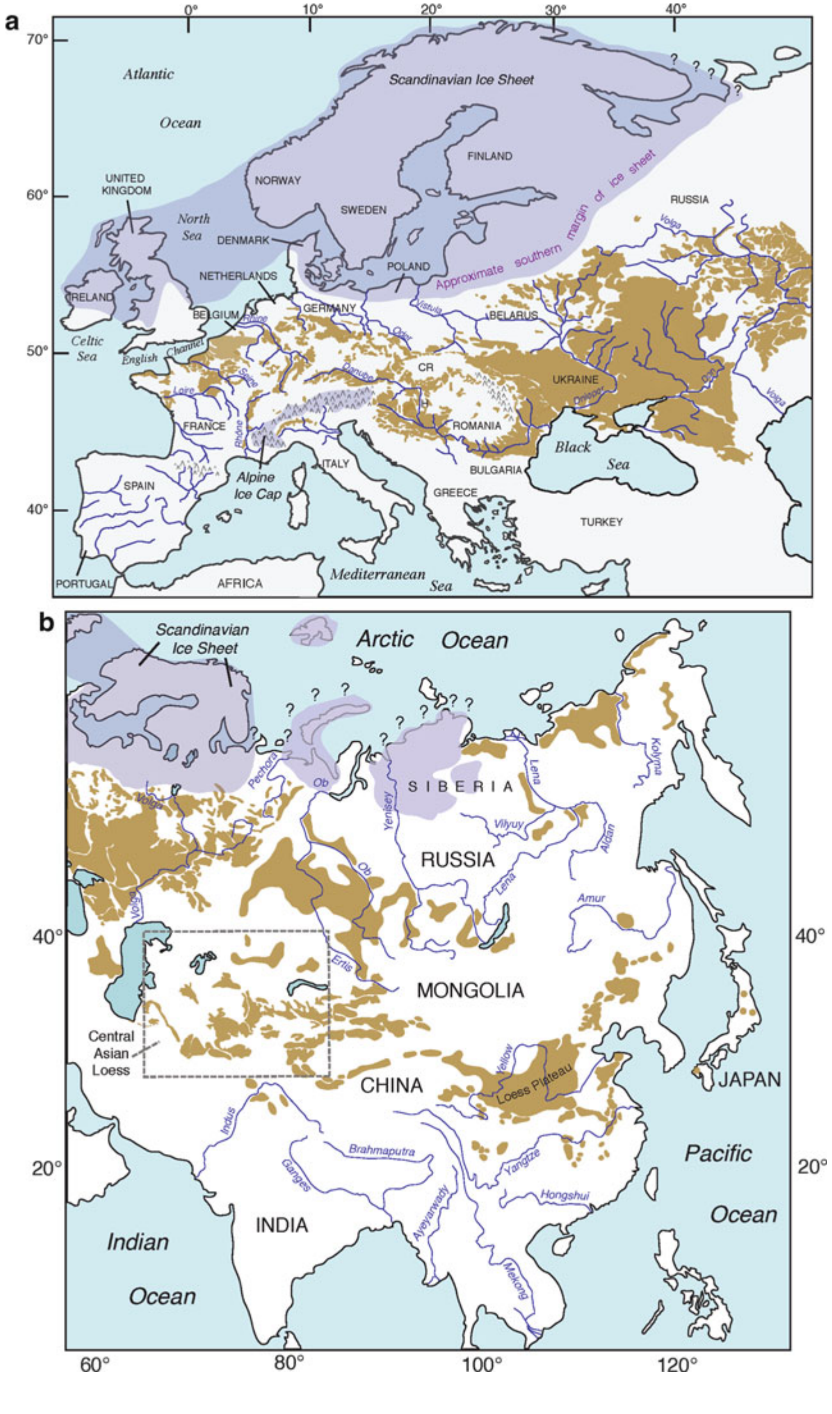
Loess lacks many of the Quaternary paleoecological indicators that are commonly used in lacustrine or marine sediments, such as pollen, diatoms, ostracodes, radiolaria, or foraminifera. Furthermore, it is rare for mammalian fossils to be preserved in loess, although Alaska (USA) is an important exception to this generalization (Péwé 1975). Fortunately, it is common for the shells of land snails to be preserved in loess, and they are abundant in China, Europe, and North America (see Liu 1985; Rousseau 1991; and Rossignol et al. 2004 for examples). 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.

16.8 Global Loess Deposits

16.8.1 Europe

Loess is extensive over much of Europe (Fig. 16.3a; see also Haase et al. 2007; Rousseau et al. 2007a). Although there is no source for loess at present, during the last glacial period, potential sources included glaciogenic silt from the ice sheets on Ireland, the United Kingdom, and Scandinavia, plus smaller ice caps at lower latitudes on mountain ranges such as the Alps, the Pyrenees, and the Vosges. In addition, the continental shelf areas of the present English Channel, Celtic Sea, and the North Sea were subaerially exposed due to lowered sea level and were potential dust source areas.

European loess deposits are distributed over three main zones (Fig. 16.3a). Eastward to about longitude 15° east, loess is found mostly (and is thickest) in


a
Atlantic
Ocean
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FINLAND
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UNITED KINGDOM
North Sea
DENMARK
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POLAND
IRELAND
BELGIUM
GERMANY
BELARUS
RUSSIA
Approximate southern margin of ice sheet
Celtic Sea
English Channel
CR
UKRAINE
FRANCE
ROMANIA
Black Sea
SPAIN
Alpine Ice Cap
ITALY
BULGARIA
GREECE
TURKEY
PORTUGAL
AFRICA
Mediterranean Sea
b
Scandinavian Ice Sheet
Arctic Ocean
SIBERIA
RUSSIA
MONGOLIA
Central Asian Loess
CHINA
Loess Plateau
JAPAN
Pacific Ocean
INDIA
Indian Ocean

a latitudinal band at about latitude 50 °N, between the continental ice sheets to the north and the Alpine glaciers in the south. Between longitudes 15° and 25° east, the thickest loess sequences are mostly located south of the Carpathian arch. Finally, eastward from 25° east, the loess deposits are distributed in a broader domain, corresponding to the wide Ukrainian and Russian plains. The loess deposits show a distribution in close proximity with the major European rivers such as the Seine, the Somme, the Rhine, the Danube, and the Dnieper.

Focusing on the past ~40 ka, the Nussloch loess section, south of Heidelberg, Germany, shows the most detailed and expanded record of this time interval (Fig. 16.7). The Nussloch quarry is located at N49°19′ and E8°43′ and is situated on the Odenwald Plateau, above the Rhine Valley (Antoine et al. 2001). The loess accumulated through elongated structures described as greda, the main dunelike morphology being built during the last glacial period, above the Arctic brown paleosol named Lohne Boden and dated between 34 ka and 40 ka by luminescence (Rousseau et al. 2007a, b).

The stratigraphy of the last glacial period at Nussloch shows that there are a minimum of eight tundra gley paleosols (Antoine et al. 2009a, b). The alternation of loess and tundra gley paleosols is interpreted as a series of loess–paleosol doublets (Rousseau et al. 2002), and such stratigraphic successions are observed from one dunelike landform to another (Antoine et al. 2009a, b; Rousseau et al. 2007a, b). The use of a combination of ^{14}C (Hatté et al. 1999) and luminescence (Lang et al. 2003) dating techniques demonstrates that the last glacial period interval, corresponding to the upper 13 m of the 18 m-thick last climate cycle sequence, lasted between ~40 and ~15 ka. Thus, the sequence at Nussloch shows a very high sedimentation rate over the last glacial period, although the tundra gley paleosols show that it was episodic. This succession of loess–paleosol doublets was correlated with the Greenland interstadial–stadial succession from DO events 8–2.

The upper Pleistocene record preserved in the Stayky (N50°05.65′, E30°53.92′) loess sequence, located 1,800 km westward from Nussloch, south of Kyiv, along the Dnieper River in Ukraine, shows a similar pattern, a succession of loess–paleosol doublets, corresponding to the same time interval (Fig. 16.7), with alternating dry-cold and wet-cool intervals (Rousseau et al. 2011). Moisture conditions are nevertheless lower than in Nussloch, as the paleosols are mostly expressed as embryonic soils, with only two tundra gleys being identified. Nevertheless, even though Nussloch and Stayky are distant from one another, grain size variations show similarities at both localities.

Fig. 16.3 (**a**) Distribution of loess in Europe (Redrawn in simplified form from Haase et al. (2007)). Also shown are major rivers (*solid blue lines*) and the approximate extent of the Scandinavian ice sheet (*light purple*) during the last glacial period (*thick dashed line*) (Simplified from Flint (1971)). *CR* Czech Republic, *H* Hungary. (**b**) Distribution of loess in Asia (Compiled from Velichko et al. (1984, 2006), Liu (1985), Dodonov (2007), and Frechen et al. (2009a)). Note: loess is also reported for Japan (Watanuki et al. 2005; Matsu'ura et al. 2011), but distribution maps are not shown in those reports. Ice sheet extents during the last glacial period (*light purple*) are approximate (Redrawn from Flint (1971))

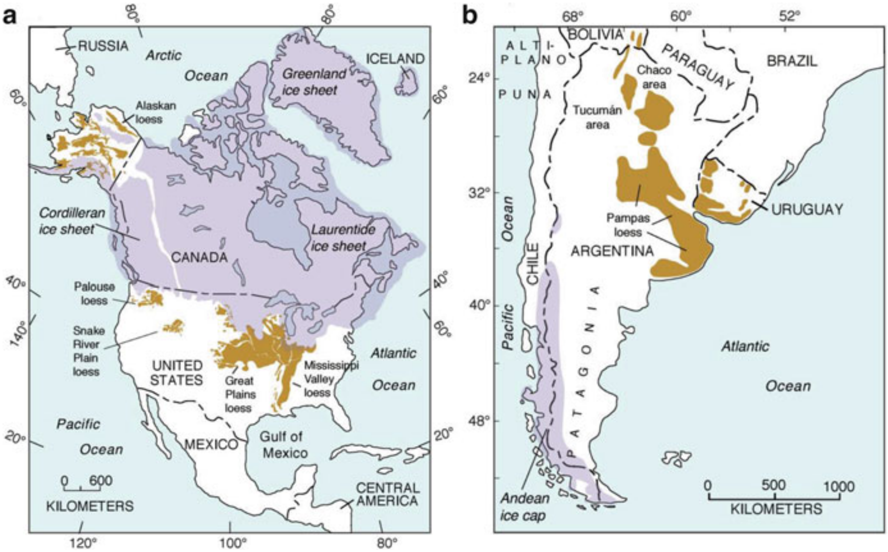

Fig. 16.4 (**a**) Distribution of loess in North America and the extent of ice sheets during the last glacial period (*light purple*) (Redrawn from Péwé (1975), Bettis et al. (2003), Busacca et al. (2004), and sources therein). (**b**) Loess distribution in South America and ice extent (*light purple*) during the last glacial period (Redrawn from Zárate (2003, 2007) and sources therein)

At lower latitudes in Europe, thick loess deposits have been described in the Carpathian basin along the Danube River, corresponding to the succession of several glacial–interglacial cycles (Markovic et al. 2006, 2009). The stratigraphy is much different than is typically observed elsewhere in Europe, with the appearance of a rather homogenous period of loess deposition (Antoine et al. 2009a), including an absence of the loess–paleosol doublets identified at localities in the 50 °N latitude loess belt. The environmental conditions appear to have been much drier during the whole last climate cycle, with conditions again allowing the occurrence and development of C_4 plants, indicative of vegetation living under severe moisture stress (Hatté et al. 2013).

16.8.2 Africa and the Middle East

Loess in Africa and the Middle East is not as extensive and thick as in Europe and in North America: it is patchy in nature (Fig. 16.6). Yet loess is the parent material for some of the most fertile soils in these regions. A few characteristics are common to all reported desert loess sites in Africa and the Middle East (following Crouvi et al. (2010)): (1) loess bodies are located in semiarid to subhumid climate

Fig. 16.5 (**a**) Map of Australia showing the approximate areas with widespread fine-grained loess (parna) deposits and patchy to isolated loess deposits (this study), localities where dust additions to soils are documented, and last glacial maximum dust additions to offshore areas ("LGM dust") (Compiled by Hesse and McTainsh (2003)). Also shown is the distribution of aeolian sand (stippled areas) in Australia, with inferred paleowind directions (All from Bowler et al. (2001)). (**b**) Distribution of loess in New Zealand (Redrawn from Eden and Hammond (2003))

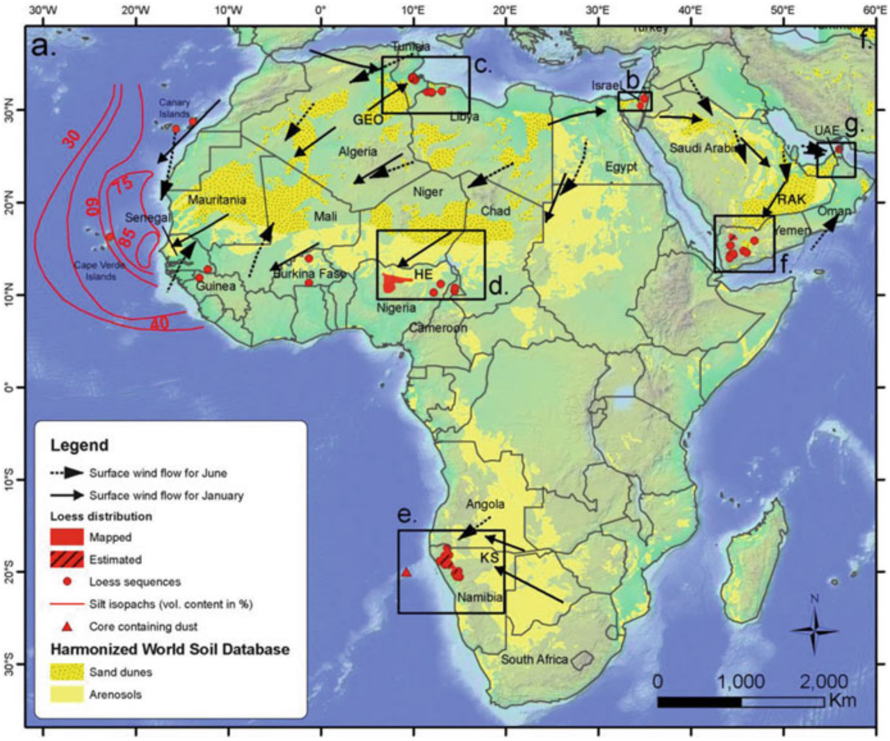

Fig. 16.6 (**a**) Spatial distribution of loess in Africa and the Middle East, active sand seas, and Arenosols (sandy soils) (From Crouvi et al. 2010 and references therein). Near-surface dominant wind directions for January and June are based on Breed et al. (1979). Red contours are content of silt (24 μm mode) in oceanic sediments off the West Africa coast deposited during the last glacial maximum (Sarnthein et al. 1981, see also Chap. 17). *Black rectangles* mark the location of well-studied loess sites in these regions mentioned in the text and in Crouvi et al. (2010): (**b**) Israel (Negev), (**c**) Tunisia and Libya, (**d**) Nigeria, (**e**) Namibia, (**f**) Yemen, and (**g**) the UAE. Abbreviations: *GEO* Grand Erg Oriental, *HE* Hausaland Erg, *KS* Kalahari Sands, *RAK* Rub' al Khali

regions; (2) at most sites, loess covers an area of 10^3–10^4 km^2; (3) loess sediments are dominated by coarse silt to very fine sand grains, with median grain size ranging from 50 to 80 μm; in some sites, the particle size distribution (PSD) is reported to be tri- or bimodal; (4) the loess bodies are generally characterized by calcic soils; (5) loess mineralogy is mostly quartz and feldspars, with various amounts of carbonate, depending on the degree of soil development in the loess; (6) in most sites, the underlying lithologies are inconsistent with the presence of quartz in the loess and suggest an external source for the silt; (7) the shapes of particles are reported as subangular to angular for most regions; and (8) most loess bodies were deposited during the last glacial period (∼110–10 ka).

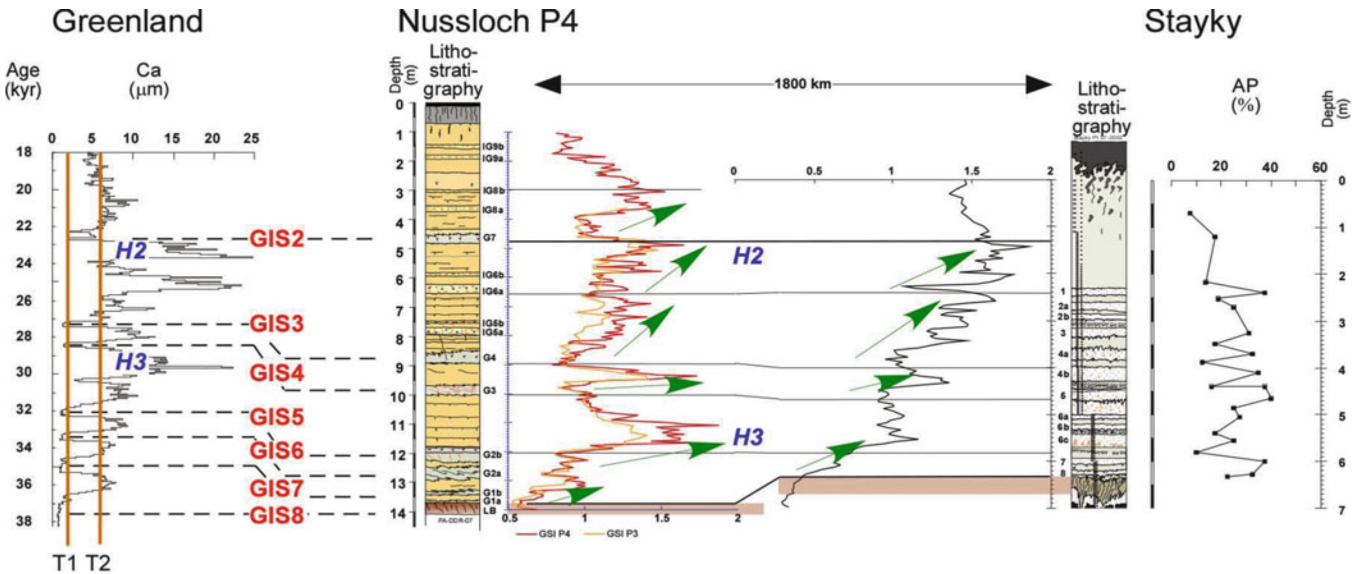

Fig. 16.7 Comparison between the grain size index (GSI) records in Nussloch (P3 and P4 sequences) (After Rousseau et al. 2007b) and in Stayky (Rousseau et al. 2011). Identification of similar cycles (marked by the *green arrows*) and proposed correlation between the two continental records, supported by IRSL dates, and pollen characteristics (arboreal pollen (AP) percentages) of the embryonic soils. Correlation between the Greenland GRIP dust record (Johnsen et al. 2001) and the Nussloch record according to Rousseau et al. (2007b), with GIS 8 correlated with the Nussloch Lohner Boden (LB). H3 and H2 correspond to marine Heinrich events 3 and 2 in the Greenland and European records. G1–7 and IG5–9 are the identified tundra gleys or oxidized horizons in Nussloch (From Rousseau et al. 2011)

The best-studied desert loess in northern Africa is located on the carbonate-rich Matmata Plateau in southern Tunisia (Coudé-Gaussen 1987; Coudé-Gaussen et al. 1987; Coudé-Gaussen and Rognon 1988; Coudé-Gaussen 1990; White et al. 2002; Dearing et al. 2001). The Tunisian loess covers an estimated area of ~4,000 km^2 and reaches thicknesses of up to 20 m. On the basis of radiocarbon ages, Coudé-Gaussen et al. (1987) showed that the age of the Tunisian loess ranges from >43 to 10 ka, whereas a chronology based on optically stimulated luminescence (OSL) (Dearing et al. 2001) suggests that the lower part of this loess is much older (250–100 ka). Loess deposits are also located on a carbonate-rich mountain range in northwestern Libya, between the Jefera Plain to the north and the Tripolitanian Plateau to the south. These deposits are considered to be a continuation of the Tunisian loess (Coudé-Gaussen 1987).

The best-known loess in the Sahel of Africa is the informally named Zaria loess, located on the Kano Plains in central-northern Nigeria (McTainsh 1984, 1987). This is probably one of the largest desert loess regions known in the world, covering an area of 41,000 km^2 and located today in a tropical climate zone. Loess PSD is mainly trimodal, with modes at 75 μm, 44 μm, and <2 μm (McTainsh 1984). OSL dating of the loess indicates an age of 37–10 ka (Stokes and Horrocks 1998). Scattered reports from other Sahelian countries suggest the presence of a noncontinuous loess belt, oriented west to east from southern Senegal through Guinea, Mali, Burkina Faso, Niger, and Nigeria to northern Cameroon; loess-like deposits are also found on the Canary Islands (Figs. 16.1c and 16.6).

Loess in southern Africa is found mainly in northwestern Namibia, where it is located on a vast area between the Great Escarpment to the coast, and it is characterized by variable underlying lithologies (Eitel et al. 2001, 2006; Brunotte et al. 2009). On the basis of the carbonate content and the heavy-mineral assemblage of the loess, Eitel et al. (2001) suggested that the source of the loess was a combination of exposed calcretes from the east and silt from local metamorphic and volcanic rocks. Crouvi et al. (2010) suggested that the main sources of quartz silt in the loess are the nearby quartz-rich Kalahari Sands that lie only a few tens to hundreds of kilometers to the east and southeast of the loess. Linear dunes in these sands are oriented east–west to east–southeast–west–northwest, suggesting an easterly wind regime when the dunes were formed; these easterly winds currently prevail in the region (Fig. 16.6). Similar to the Sahelian loess, the Namibian loess stretches westward into the Atlantic Ocean, as finer silt deposits from marine cores are reported off the Namibian coast (e.g., Stuut et al. 2002, see also Chap. 17). There is a good temporal correlation between the period of sand-dune activity, loess accumulation, and silt deposition off the Namibian coast (Crouvi et al. 2010).

The most prominent loess in the Middle East is located in the Negev desert, southern Israel, covering an area of ~5,500 km^2 (Figs. 16.1d and 16.6). It mantles most of the exposed carbonate bedrock in the northern Negev and fills depressions and valleys farther south in the central Negev highlands (Yaalon and Dan 1974). The PSD of the loess is bimodal (50–60 μm and 3–8 μm), with a general upward increase of the coarse mode versus the fine mode in all sequences that have been studied (Crouvi et al. 2008, 2009). Bulk mineralogy is quartz, calcite, phyllosilicates, and feldspars, whereas the coarse mode is composed mostly of quartz and feldspars (Crouvi et al. 2008). Recent OSL ages suggest that the upper Pleistocene Negev loess started accumulating at 95 ka (Crouvi et al. 2008, 2009).

Crouvi et al. (2008, 2009) suggested that the main sources of the coarse silt grains in the loess are the adjacent sand dunes in western Negev and Sinai that advanced eastward during the late Pleistocene. These studies based their suggestion mainly on the observation that the increase of the PSD fraction of coarse silt grains in the loess (composed mainly of quartz) is temporally associated with the incursions of adjacent sand dunes upwind from the loess. Elsewhere in the Middle East, loess is found in northwestern Yemen (Fig. 16.6), on the volcanic plateau of Sana (Grolier and Overstreet 1978; Nettleton and Chadwick 1996; Wilkinson 1997), and in the United Arab Emirates (Goudie et al. 2000).

In a recent compilation, Crouvi et al. (2010) suggested that for all reported loess in Africa and the Middle East, sand seas supply the coarse silt for desert loess, based on the following observations: (1) all loess sites are spatially associated with adjacent sand seas (Fig. 16.6) and are located only a few tens of kilometers from sand dunes, within the range for aeolian transport of coarse silt grains (Tsoar and Pye 1987); (2) there is a good agreement between the mineralogical composition of the loess and that of the sand dunes; (3) according to the paleowind direction interpreted from the orientation of the sand dunes, all loess sites are located downwind of the adjacent sand seas; (4) there is evidence of decreases in grain size downwind from the sand dunes toward the loess in a few sites; and (5) the estimated ages of loess deposition and dune activity generally overlap, where, in most cases, sand-dune activity preceded loess deposition, and no data indicate loess deposition preceding sand-dune activity.

The identification of sand dunes as the source for coarse silt grains in downwind loess deposits can support or rebut different hypotheses for the generation of silt in deserts. Because, in most places, sand dunes are composed of well-sorted sand grains, with limited amounts of coarse silt grains, this observation strengthens the hypothesis raised in the past that aeolian abrasion of sand grains is one of the important mechanisms for generating silt grains in deserts (e.g., Whalley et al. 1982; Crouvi et al. 2010; Enzel et al. 2010). The reported angularity of desert loess grains supports this hypothesis. Laboratory experiments show that aeolian abrasion of sand grains produces both coarse and fine silt grains (e.g., Whalley et al. 1982; Bullard et al. 2004). Given the absence of glacial activity near most low-latitude deserts, even during the late Pleistocene, and the large sand seas there (Fig. 16.6), it is reasonable that spalling might be the dominant source of silt, at least locally.

16.8.3 Asia

Loess mantles extensive regions in Asia, especially in the largest midlatitude arid–semiarid zone in the Northern Hemisphere (Fig. 16.3b). The most widespread loess deposits in Asia occur in China, centered in the Loess Plateau, where the oldest loess can be dated back to 22–25 Ma (Guo et al. 2002; Qiang et al. 2011), and loess can be hundreds of meters thick, as at Lanzhou in the western Loess Plateau (Burbank and Li 1985). Loess is also found in Central Asia including Tajikistan, Kyrgyzstan, Turkmenistan, Uzbekistan, and Kazakhstan. Regardless of where the loess is found in Asia, all loess bodies are bordered by or in the downwind areas of gobi (stony desert) and sand deserts.

Loess in China is widespread between latitudes 34–45 °N and longitudes 75–130 °E (Fig. 16.3b). Although the most continuous loess cover is in the central part of northern China, forming the Loess Plateau, loess deposits also occur on pediments in the forelands of high mountains in northeastern China. On the Loess Plateau, the thickness of loess varies from tens to hundreds of meters, found at elevations ranging from 1,000 to 1,500 m. In northwestern China, loess is found mainly blanketing mountain slopes, with thickness usually less than tens of meters, but the elevation where it is found can be up to 4,000 m.

In Central Asia, loess deposits are adjacent to mountain regions and dominantly cover piedmonts and hills (Dodonov 1991, 2007). In contrast to the Chinese Loess Plateau, loess in Central Asia mostly accumulates on the windward slopes of the Central Asian orogenic belt (including the Tian Shan, Kunlun, Hindu Kush, and Pamir Mountains), where loess can be found at elevations of up to 2,500–3,000 m (Dodonov 1991). Generally, loess deposits in Central Asia are several tens of meters thick, except in certain regions, such as Tajikistan, or in the vicinity of Tashkent, where the loess strata can be up to 100–200 m (Dodonov 1991; Ding et al. 2002a).

For Chinese loess, the basal age of the Quaternary loess–paleosol successions is near the Gauss/Matuyama (G/M) geomagnetic polarity boundary (Heller and Liu 1982; Liu 1985), with an age of about 2.58 Ma. More recently, the Neogene Red Clay (Fig. 16.1b), also on the Loess Plateau, has now been demonstrated to be aeolian. The latter deposits are discontinuously overlain by the Quaternary loess–soil successions, being usually younger than 8 Ma in most sites (Ding et al. 1998; Qiang et al. 2001), with the exception of the Qinan section that extends to 22 Ma (Guo et al. 2002). The most recent study in the Junggar basin of northwestern China reveals aeolian deposits of 24 Ma (Sun et al. 2010), whereas a long core taken on the western Loess Plateau reveals aeolian dust accumulation that can be dated back to 25 Ma (Qiang et al. 2011). In Central Asia, stratigraphic and chronological studies have previously shown that loess began to accumulate about 2–2.5 Ma ago and the loess–soil sequences at different sites can be correlated with each other (Dodonov 1991; Dodonov and Baiguzina 1995).

For the most extensive and thickest loess deposits on the Loess Plateau, a vast provenance of northwestern China had been proposed (Liu 1985). However, multiple isotopic, chemical, and mineralogical data demonstrate that the loess deposits on the Loess Plateau are mainly derived from the gobi deserts that lie to the north of the Loess Plateau, whereas aeolian dust entrained from the three inland arid basins (the Tarim, Junggar, and Qaidam basins) of northwestern China contributes very little to the loess deposits on the Loess Plateau. Dust from these basins accumulates mainly on the piedmont forelands of high mountains surrounding the basins (Sun et al. 2001; Sun 2002a, b). Moreover, although these gobi and sand deserts are regarded as the main source regions, they serve as dust and silt holding areas rather than dominant producers. The mountain processes (including glacial grinding, frost weathering, salt weathering, tectonic processes, and some fluvial comminution) in the Gobi Altay Mountains, Hangayn Mountains, and the Qilian Mountains have played an important role in producing the vast amounts of loess-sized material for forming the Loess Plateau (Sun 2002a).

Sun et al. (2007) argued that fine silt- to clay-sized quartz in the northwestern deserts are heterogeneous and derived mainly from the nearby high-altitude mountains in East Asia, whereas the eastern deserts in China mainly have a local source. Based on the luminescence sensitivity variations of quartz grains from Chinese deserts, four regional groups of Chinese deserts can be distinguished including the eastern, central, western, and northwestern deserts. The different luminescence sensitivity signals are dominantly related to the rock types of mountains surrounding or adjacent to the deserts (Lü and Sun 2011).

Temporal variations of loess provenance have also been studied. Based on temporal variations in Sr, Nd, and Pb isotopes and trace element concentrations within airborne dust on the central Loess Plateau (Sun 2005; Sun and Zhu 2010), a distinct change in source occurred at about 2.6 Ma. This change in the source of aeolian dust at 2.6 Ma is considered to be coincident with the initiation of Quaternary glaciation in the Northern Hemisphere. The dramatic climatic cooling induced glacial grinding, which plays an important role in modifying the source material of the dust.

Loess accumulation in Central Asia is closely linked to the geographic and atmospheric conditions in the area. The great deserts such as Karakum, Kyzylkum, and Sary-Ishikotrau are situated directly to the west and northwest of the loess region, covering the windward piedmont forelands and river valleys of Tian Shan and the Pamir Plateau (e.g., Dodonov and Baiguzina 1995; Finaev 1995; Ding et al. 2002a). In addition, airborne dust can be also transported to Iran and accumulate as loess (Asadi et al. 2012). Paleowinds in northeastern Iran were dominated by northerly or northeasterly winds blowing from Central Asia, as suggested by the delineation of dune fields in the Karakum Desert, in Turkmenistan (Rozychi 1991; Letolle and Mainguet 1993), and by the spatial distribution of loess deposits along Kopeh Dagh (Kehl 2009).

Loess–paleosol sequences on the Loess Plateau of north-central China (Fig. 16.1a) have provided abundant information about regional and global climate changes during the Quaternary (Heller and Liu 1982; Kukla and An 1989). The most important studies of the orbital-scale paleoclimatic record on the Loess Plateau were completed by Ding's group (Ding et al. 1993, 1994, 2002b). Based on detailed pedostratigraphy and magnetostratigraphy of the Baoji section, thirty-seven pedostratigraphic units are identified, representing thirty-seven major cold-to-warm climatic cycles in the past 2.5 Ma (Ding et al. 1993).

For the Central Asia loess, the best long-term paleoclimatic record is the Chashmanigar loess section (Fig. 16.8) of southern Tajikistan (Ding et al. 2002a; Yang and Ding 2006; Yang et al. 2006). This section is about 200 m thick and consists of an alternation of loess and paleosol layers with a basal age of about 1.77 Ma (Ding et al. 2002a). The high-resolution magnetic susceptibility,

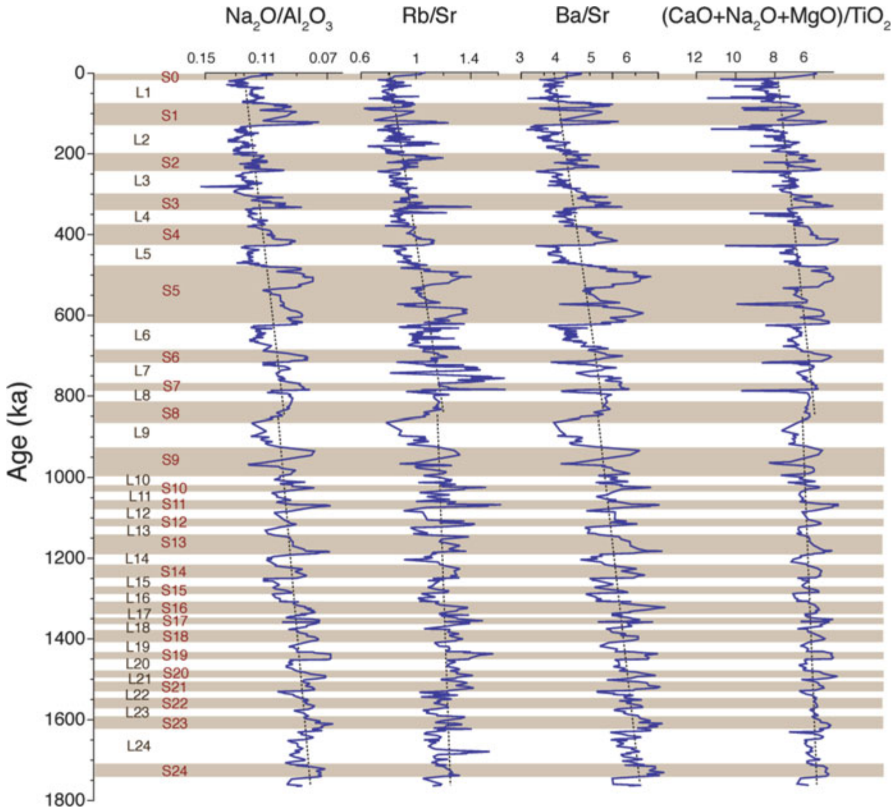

Fig. 16.8 Changes in Na_2O/Al_2O_3 (weight–percent ratio, not molar ratio), Rb/Sr, Ba/Sr, and $(CaO + Na_2O + MgO)/TiO_2$ (weight–percent ratio, not molar ratio) at loess–paleosol section at Chashmanigar, Tajikistan. The timescale is taken from Ding et al. (2002b). The *shaded zones* indicate interglacials, as represented by paleosols. Greater alteration of weatherable minerals in paleosols can be seen in these plots (note reversed horizontal scales on Na_2O/Al_2O_3 and $(CaO + Na_2O + MgO)/TiO_2$ plots). The *dashed lines* are linear fits of each curve for different time intervals (Redrawn from data in Yang et al. (2006))

grain size, and color reflectance time series all show astronomical periodicities during the Pleistocene. The mid-Pleistocene climate transition, characterized by a shift of dominant climatic periods from 41 to 100 kyr at about 1.0–0.8 Ma, is clearly documented in these proxy records (Ding et al. 2002a). It is suggested that alternations of loess and soil horizons in Central Asia were controlled by global ice volume variations. The long-term chemical weathering history of this section (Fig. 16.8) indicates a decreasing chemical weathering trend since 0.85 Ma (Yang et al. 2006). This event may be causally related to the expansion of Northern Hemisphere ice and/or the regional tectonic uplift of high mountains in Asia since the mid-Pleistocene.

16.8.4 Australia and New Zealand

Despite the proximity of the two countries, the understanding and characterization of loess in Australia and New Zealand are vastly different, due to differences in landscape processes, paleo- and contemporary climatic regimes, and sedimentological nomenclature. Whereas in the generally cooler, wetter New Zealand, loess is widespread and very well described, in Australia there is a scarcity of published work describing "loess" and a general view that soil derived from fine-grained aeolian sediment is quite restricted in distribution. Undoubtedly, the dominance of the cold-climate loess paradigm throughout the twentieth century entrenched the view that loess was largely absent from the Australian continent. But over the past two decades, a counterview has emerged that the hitherto described "parna" (Butler 1956) should be regarded as clayey, hot-climate loess (Dare-Edwards 1984; Hesse and McTainsh 2003; Haberlah 2007). In this chapter, parna will be regarded as fine-grained loess.

At present on the Australian continent, there are two major wind paths emanating from the arid interior. One of these extends in an east–southeasterly direction across the eastern states to the Tasman Sea, and the other extends in a northwesterly direction across Western Australia to the Indian Ocean (Fig. 16.5a). It is along the so-called southeastern dust path that the majority of the identified Australian loess deposits exist. In particular, southern New South Wales and northern Victoria have prominent areas of red, clayey, and often calcareous soil derived from clayey loess (parna) deposits.

The fine-grained material that dominates Australian loess deposits is characterized by a relatively high clay content; the presence of coarse, silt-sized quartz; a strong red to yellow color; and a variable presence of calcium carbonate. Indeed, it is the combination of these attributes in soil profiles over a variety of lithologies that first led Butler (1956) to identify and popularize the concept of "parna" on the Riverine Plain. Mineralogically, these clayey loess deposits are dominated by kaolinite, illite, and quartz (Beattie 1970), with inclusions of calcium carbonate being more prevalent at the arid–semiarid western end of the deposition zone.

The current understanding of the genesis of Australian parna is that during arid and windy glacial periods of the Quaternary, fine-grained materials were winnowed from the sand hills, playas, and floodplains of what are now western New South Wales, northwestern Victoria, and eastern South Australia and deposited 300–500 km downwind as a blanket of sediment. A central tenet of this model is that while the transported material contained considerable clay-sized particles, it was transported in the form of silt-sized pellets accompanied by quartz companion grains. Unfortunately, there is a dearth of reliable age estimates for loess deposits in eastern Australia.

In New Zealand, loess mantles are widely distributed across both the North and South Islands, with McCraw (1975) estimating that 10 % of the country's land mass ($\sim$26,000 km^2) is covered by loess at least a meter thick (Fig. 16.5b). The range of loess mantle thickness is 0.5–6.0 m (Eden and Hammond 2003), but the thickest mantles are located in the southern parts of the North Island and the eastern and southern parts of the South Island (Fig. 16.5). On the North Island, loess deposits are most prominent in the Manawatu region, where old terraces of cold-climate floodplains have been mantled by dust from nearby braided streambeds (Molloy 1998), and in the inland basins of Hawke's Bay. On the South Island, loess deposits are most prominent on the high terraces of the Canterbury Plain, the North Canterbury and South Canterbury downlands, the Banks Peninsula, and the South Otago downlands and Southland Plains (Molloy 1998).

New Zealand loesses tend to exhibit more "classical loess" features: silty loam texture, pale colors, and weak/massive structure (Fig. 16.2d). In many localities, loess facies are characterized by multiple paleosol horizons and/or inclusions of tephric layers (Eden and Hammond 2003), while fragipans are a feature of some relatively unaltered loess deposits. Common minerals in New Zealand loess deposits and soil developed therein include quartz, feldspars, micas, vermiculite, kaolinite, and halloysite. Where volcanic ash has contributed significantly to the loess deposit, ferromagnesian minerals, allophane, and volcanic glass may be prominent (McCraw 1975; Molloy 1998; Eden and Hammond 2003).

Most loess in New Zealand has been produced by cold-climate processes, such as freeze/thaw action and glacial grinding, as well as river abrasion, comminution, and sorting (Eden and Hammond 2003). The North Island loess deposits are nearly all products of fluvial processes and the winnowing of dry streambeds, while in the South Island cold-climate loess processes operated in the Southern Alps during the Quaternary glacial periods, supplying silt-sized sediment to the rivers of the eastern half of the island for eventual winnowing and transport to adjacent plains and downlands. A further form of loess, tephric loess or volcanic loess, also occurs in and near the central volcanic region of the North Island (Eden and Hammond 2003), but the significance of this tephric parent material is perhaps greatest from a chronological standpoint. Volcanic ash conveniently identifies (and separates) the Ohakea loess, which was laid down across the Manawatu between 25,000 and 12,000 years ago and which acts as the parent material for the present-day soils (Molloy 1998). In the South Island of New Zealand, accretion rates and ages of loess deposits have been estimated through the identification of the Kawakawa Tephra (deposited ~26,0000 years before present), thermoluminescence techniques, and ^{14}C dating (Eden and Hammond 2003).

16.8.5 South America

South American loess presents a broad geographic distribution (Fig. 16.4b) extending across the Chaco–Pampean Plain of Argentina and neighboring areas of Uruguay, southern Brazil (Rio Grande do Sul), Paraguay, and the eastern Bolivia lowlands (Zárate 2003). Loess is extensive in the western Chaco (Iriondo 1997) and forms a wide belt in the eastern Pampas, grading into sand mantles and dune fields toward the west and southwest. Thick loess deposits are located in the sub-Andean mountainous area of northwestern Argentina (Tucumán); they also occur in the highland plains of Sierras Pampeanas of Córdoba and San Luis. In addition, loess has been reported in Tierra del Fuego and the eastern Andean piedmont (Zárate 2003), while Holocene peridesert loess has been reported in the Atacama Desert of Peru (Eitel et al. 2005).

Much of the knowledge of South American loess comes from the Pampean Plain where the deposits consist of complex stratigraphic sequences composed of primary loess and loess-like (loessoid) deposits that are usually much more abundant (Fig. 16.2c; Zárate and Blasi 1993; Zárate et al. 2009). Loess deposits are commonly interlayered with fluvial gravels and/or colluvial deposits along the piedmonts of the southern Buenos Aires ranges (Ventania, Tandilia) and the Pampean ranges of Córdoba and San Luis provinces. Carbonate accumulations of variable morphology and genesis are common in the loess sequences. Fossil vertebrate remains are very common, together with abundant bioturbation features of both vertebrates and invertebrates (Zárate 2007).

The Pampean stratigraphic record dates back to the late Miocene (∼12–10 Ma). The thickest (∼40–50 m) Quaternary loess and loess-like deposits are located in the northern Pampas with only the uppermost 10–15 m exposed. The loess sedimentation process during the Neogene–Quaternary was characterized by the occurrence of several pulses of landscape reactivation marked by major erosional episodes (Folguera and Zárate 2011).

The chronology of the Pampean loess sequence traditionally has been estimated on the basis of their vertebrate fossil content, being subdivided into several biostratigraphic units (land mammal ages; see Marshall et al. 1983) later redefined as stage–ages (Cione and Tonni 1995). In recent years, numerous luminescence dates were obtained from several upper Quaternary sections of the northern and southern Pampas (e.g., Kemp et al. 2006; Frechen et al. 2009b; Kruck et al. 2011).

The loess–paleosol sequences in the mountains of the Tucumán region (Kemp et al. 2003) are situated at an altitude between 1,800 m and 2,500 m asl and west of the western Chaco Plain (Fig. 16.4b). This sequence, which exhibits a much higher stratigraphic resolution than the Pampean successions, consists of a thick (∼40–50 m) record of loess and reworked loess. The deposits, rich in vertebrate fossil remains, are characterized by the occurrence of numerous (28–32) discrete paleosols (Zinck and Sayago 2001; Schellenberger and Veit 2006).

The Pampean loess deposits are chiefly of volcanoclastic composition, with particles made up of volcanic lithic fragments (basaltic, andesitic, and rhyolithic rocks), volcanic glass shards, feldspar (mainly orthoclase), plagioclase (albite to labradorite), and quartz, usually with percentages lower than 20 %. The mineralogical and geochemical compositions of loess and loess-like deposits (Teruggi 1957; Smith et al. 2003) suggest that the explosive, volcanic Andes Cordillera is the main loess source area, including the direct input of volcanic particles as well as discrete tephra layers. The mountain loess of Tucumán is thought to be derived from the northwestern Argentinian/southern Bolivian Andes and the Altiplano

(Schellenberger and Veit 2006). Secondary source areas of loess are present across the region that comprise the Pampean ranges of Córdoba and San Luis, the Paraná River basin, the southern Buenos Aires ranges (Ventania and Tandilia), the ranges and outcrops of Paleozoic and Mesozoic rocks of the south-central Pampas, and likely the igneous and metamorphic rocks of southern Uruguay (Zárate 2003, and references therein). The accumulation of loess has been explained through a combined mechanism of fluvial and aeolian transport from the Andes to the eastern lowlands.

The loess–paleosol pattern of South America, even back to the Pliocene, is interpreted to be the result of cyclic climatic conditions, with loess accumulating during glacial intervals and soils developing during periods of climatic amelioration, interglacials and interstadials (Kemp and Zárate 2000). Recently, Rabassa et al. (2011) reported late Pliocene glacial deposits in the northern Patagonian Andes, making more plausible the linkage between the loess accumulation and glacial conditions at this time interval. The mountain Loess Plateau of Tucumán and the northern Pampas of Buenos Aires province provide long and quasi-continuous records that have permitted inferences of the environmental history during a considerable time span of the Pleistocene.

The accumulation of loess deposits was widespread across different localities of the northern and southern Pampas between ∼30 ka and ∼10 ka. The significant aeolian activity during this interval is also suggested by OSL ages that indicate active dunes in the western sand-dune fields that fringe the eastern Pampean loess belt (Tripaldi and Forman 2007; Tripaldi et al. 2011). A major decrease of the loess accumulation rate occurred at the Pleistocene–Holocene transition (∼12–9 ka) when soil formation began to dominate in several areas of the eastern Pampas, giving way to the development of modern soils. While the Holocene is basically documented by soil formation in the eastern Pampas, some settings of the southern Pampas (Tandilia range, Bahia Blanca) document loess accumulation between ∼5 and 4 ka.

Southern South America has been proposed as the likely source area of the dust found in Antarctica (Delmonte et al. 2004, see Chap. 18). Patagonia, the Chaco–Pampean region, and the continental shelf are the specific areas considered to be potential dust sources. Gaiero (2007) and Gaiero et al. (2013) point out that isotopic data indicate that Patagonia and the Puna–Altiplano Plateau could represent the most important Southern Hemisphere provenance areas for glacial dust deposited in East Antarctica.

16.8.6 North America

In North America, loess is found mostly beyond the margins of where the Laurentide and Cordilleran ice sheets and mountain glaciers advanced during the last glacial period (Bettis et al. 2003; Roberts et al. 2007). In the northwestern part of North America, loess is found in Alaska and the adjacent western parts of Yukon Territory of Canada (Muhs et al. 2003). There are also large tracts of loess in the Palouse area of eastern Washington and adjacent Oregon and the Snake River Plain and adjacent uplands of Idaho. By far, however, the greatest extent of loess is found in the mid-continent region, including the greater Mississippi River drainage basin and the Great Plains (Fig. 16.4a).

In the greater Mississippi River basin (including the Missouri and Ohio river drainage basins), south of the Laurentide ice sheet, loess is dominantly glaciogenic, although there are non-glacial contributions (Grimley 2000; Bettis et al. 2003). Thus, loess units represent glacial periods and paleosols represent interglacial or interstadial periods. To a great extent, therefore, loess deposition is a "turn-on/turn-off" process that differs from the more complex pattern seen in China. In this region, the three youngest loess units are the Loveland Loess of penultimate glacial age, the Roxana Silt of early last glacial age, and the Peoria Loess of late last glacial age. Dating of Peoria Loess to the last glacial period, about 25,000–12,000 radiocarbon years ago, is based on studies conducted at dozens of sections (Bettis et al. 2003). Peoria Loess can reach extraordinary thickness, up to ~40 m in some sections in western Iowa (Bettis et al. 2003).

Farther west, in the Great Plains region, studies by Aleinikoff et al. (2008) and Muhs et al. (2008) show that sedimentary rock (volcaniclastic siltstone) is the most important source of silt-sized particles in the Peoria Loess of last glacial age (Fig. 16.2a). Despite the different modes of origin of Great Plains loess, radiocarbon and OSL ages indicate that Peoria Loess in the Great Plains was deposited at about the same time as Peoria Loess farther east (Roberts et al. 2003; Muhs et al. 2008). Thus, even without glaciers, the Great Plains region experienced favorable conditions for loess formation during the last glacial period. Unlike the Mississippi River basin, however, the Great Plains region also has a younger Holocene loess called the Bignell Loess.

The loess deposits in the Columbia Plateau, or "Palouse" region (Fig. 16.4a), present a very different record than those of other parts of North America. In this area, loess records may extend as far back as 1–2 Ma (Busacca 1991). The loess deposits preserve many paleosols (Fig. 16.2b), reflecting periods of nondeposition and stability between times of more active loess deposition. The timing of the deposition of loess in the Palouse region of eastern Washington differs from that for other loess deposits of North America and, indeed, the world (Busacca et al. 2004). In this area, the principal source of the loess is believed to be flood sediments of proglacial Lake Missoula, exposed during glacial maxima at least six times in the Pleistocene (Busacca et al. 2004). Thus, the production of the loess deposits is believed to peak late in the glacial cycle.

Loess is widely distributed in Alaska and adjacent Canada and is geographically the most extensive surficial deposit in the region (Fig. 16.4a). In central Alaska, studies by Westgate et al. (1990) indicate that the Alaskan loess record may extend back to ~3.0 Ma. The thicknesses of the deposits range from a few centimeters in some areas to more than 60 m near Fairbanks. Throughout Alaska, loess deposits are thickest near rivers, with thicknesses decreasing rapidly with distance away from the rivers and downwind of valley dust sources (Péwé 1975; Muhs et al. 2004). The transport and deposition of loess are processes that are still active today in Alaska, particularly along the Delta, Knik, Matanuska, and Copper Rivers, all of which drain mountain ranges with glaciers. Holocene loess is exposed in these valleys. Although there is indirect evidence for glacial-age loess in Alaska, there are surprisingly few ages that actually document last glacial-aged loess (see review in Muhs et al. 2003). Paleosols are common in central Alaskan loess, indicating that loess deposition here, like elsewhere, has been episodic.

16.9 Conclusion

Loess is aeolian sediment that is dominated by silt-sized particles. Unlike both coarser dune sand and finer-grained LRT dust, loess is relatively poorly sorted, reflecting a combination of transport processes, including saltation, low suspension, and high suspension. Loess can be readily identified in the field and has thicknesses ranging from a few centimeters to many tens of meters. It is found over large areas of Europe, Asia, South America, and North America, and smaller areas of New Zealand, Australia, Africa, and the Middle East. Most loess deposits have compositions that are similar to and reflect derivation from the upper continental crust. Loess can be derived from glacially ground rock and silt particles derived from "desert" (non-glacial) processes of rock breakup or simply inherited from silt-sized sedimentary rocks or silt-sized tephra.

Loess has distinct advantages over other Quaternary sediments for documenting climate change in that it provides a direct record of atmospheric circulation and can be dated directly by both luminescence and radiocarbon methods. Loess can be used to reconstruct paleowinds using spatial trends of thickness and particle size. Paleosols are common in loess and represent periods of little or no loess deposition. Paleosols and snails in loess can be used to reconstruct paleoclimates.

In most of Europe and many parts of North America and South America, much loess is clearly tied to glacial-sediment supplies. In both Europe and North America, however, rates of loess deposition varied within glacial periods. In many areas, the stratigraphic record is more complex than a simple correlation of loess with glacial periods and paleosols with interglacial periods. In China, neither loess deposition nor soil formation ever ceases completely, so sedimentation and pedogenesis are best portrayed as competing processes that are modulated by climate change. Still, glacial periods show higher rates of loess deposition than interglacial periods. In the Great Plains of North America, non-glacial sources of loess were available during both glacial and interglacial periods, but much greater rates of deposition occurred during glacial periods, indicating that a glacial-type climate is one that is most favorable to thick loess accumulation.

References

Aleinikoff JN, Muhs DR, Bettis EA III, Johnson WC, Fanning CM, Benton R (2008) Isotopic evidence for the diversity of late Quaternary loess in Nebraska: glaciogenic and non-glaciogenic sources. Geol Soc Am Bull 120:1362–1377

Antoine P, Rousseau D-D, Zöller L, Lang A, Munaut AV, Hatté C et al (2001) High-resolution record of the last interglacial-glacial cycle in the loess palaeosol sequences of Nussloch (Rhine Valley-Germany). Quatern Int 76(77):211–229

Antoine P, Rousseau D-D, Fuchs M, Hatté C, Gauthier C, Markovic SB et al (2009a) High-resolution record of the last climatic cycle in the southern Carpathian Basin (Surduk, Vojvodina, Serbia). Quatern Int 198:19–36

Antoine P, Rousseau D-D, Moine O, Kunesch S, Hatté C, Lang A et al (2009b) Rapid and cyclic aeolian deposition during the last glacial in European loess: a high-resolution record from Nussloch, Germany. Quatern Sci Rev 28:2955–2973

Asadi S, Moore F, Keshavarzi B (2012) The nature and provenance of Golestan loess deposits in northeast Iran. Geol J. doi:10.1002/gj.2466

Beattie JA (1970) Peculiar features of soil development in parna deposits in the eastern Riverina, NSW. Aust J Soil Res 8:145–156

Bettis EA III, Muhs DR, Roberts HM, Wintle AG (2003) Last glacial loess in the conterminous U.S.A. Quatern Sci Rev 22:1907–1946

Blatt H (1987) Oxygen isotopes and the origin of quartz. J Sediment Petrol 57:373–377

Bowler JM, Wyrwoll K-H, Lu Y (2001) Variations of the northwest Australian summer monsoon over the last 300,000 years: the paleohydrological record of the Gregory (Mulan) lakes system. Quatern Int 83–85:63–80

Breed CS, Fryberger SG, Andrews S, McCauley C, Lennartz F, Gebel D, Horstman K (1979) Regional studies of sand seas, using Landsat (ERTS) imagery. In: McKee ED (ed) A study of global sand seas. United States Geological Survey, Professional Paper 1052, Washington, pp 305–397

Brunotte E, Maurer B, Fischer P, Lomax J, Sander H (2009) A sequence of fluvial and aeolian deposits (desert loess) and palaeosoils covering the last 60 ka in the Opuwo basin (Kaokoland/Kunene Region, Namibia) based on luminescence dating. Quatern Int 196:71–85

Bullard JE, McTainsh G, Pudmenzky C (2004) Aeolian abrasion and modes of fine particle production from natural red dune sands: an experimental study. Sedimentology 51:1103–1125

Burbank DW, Li JJ (1985) Age and palaeoclimatic significance of the loess at Lanzhou, north China. Nature 316:429–431

Busacca AJ (1991) Loess deposits and soils of the Palouse and vicinity. In: Morrison RB (ed) The geology of North America vol. K-2, Quaternary nonglacial geology; conterminous U.S. Geological Society of America, Boulder, pp 216–228

Busacca AJ, Begét JE, Markewich HW, Muhs DR, Lancaster N, Sweeney MR (2004) Eolian sediments. In: Gillespie AR, Porter SC, Atwater BF (eds) The Quaternary period in the United States. Elsevier, Amsterdam, pp 275–309

Butler BE (1956) Parna – an aeolian clay. Aust J Sci 18:145–151

Cione AL, Tonni EP (1995) Chronostratigraphy and "land-mammal ages" in the Cenozoic of southern South America: principle, practices, and the "Uquian" problem. J Paleontol 69:135–159

Coudé-Gaussen G (1987) The perisaharan loess: Sedimentological characterization and paleoclimatical significance. GeoJournal 15:177–183

Coudé-Gaussen G (1990) The loess and loess-like deposits along the sides of the western Mediterranean Sea; genetic and palaeoclimatic significance. Quatern Int 5:1–8

Coudé-Gaussen G, Rognon P (1988) The upper Pleistocene loess of Southern Tunisia: a statement. Earth Surf Process Landf 13:137–151

Coudé-Gaussen G, Rognon P, Rapp A, Nihlen T (1987) Dating of peridesert loess in Matmata, south Tunisia, by radiocarbon and thermoluminescence methods. Z Geomorphol N F 31:129–144

Crouvi O, Amit R, Enzel Y, Porat N, Sandler A (2008) Sand dunes as a major proximal dust source for late Pleistocene loess in the Negev desert, Israel. Quatern Res 70:275–282

Crouvi O, Amit R, Porat N, Gillespie AR, McDonald EV, Enzel Y (2009) Significance of primary hilltop loess in reconstructing dust chronology, accretion rates, and sources: an example from the Negev desert, Israel. J Geophys Res 114, F02017

Crouvi O, Amit R, Enzel Y, Gillespie AR (2010) The role of active sand seas in the formation of desert loess. Quatern Sci Rev 29:2087–2098

Dare-Edwards AJ (1984) Aeolian clay deposits of south-eastern Australia: parna or loessic clay? Trans Inst Br Geogr NS 9:337–344

Dearing JA, Livingstone IP, Bateman MD, White K (2001) Palaeoclimate records from OIS 8.0-5.4 recorded in loess-palaeosol sequences on the Matmata Plateau, southern Tunisia, based on mineral magnetism and new luminescence dating. Quatern Int 76–77:43–56

Delmonte B, Basile-Doelsch I, Petit J-R, Maggi V, Revel-Rolland M, Michard A, Jagoutz E, Grousset F (2004) Comparing the Epica and Vostok dust records during the last 220,000 years: stratigraphical correlation and provenance in glacial periods. Earth Sci Rev 66:63–87

Ding ZL, Rutter NW, Liu TS (1993) Pedostratigraphy of China loess deposits and climatic cycle in the last 2.5 Myr. Catena 20:73–91

Ding ZL, Yu Z, Rutter NW, Liu T (1994) Towards an orbital time scale for Chinese loess deposits. Quatern Sci Rev 13:39–70

Ding ZL, Sun JM, Liu TS, Zhu RX, Yang SL, Guo B (1998) Wind-blown origin of the Pliocene red clay formation in the central Loess Plateau, China. Earth Planet Sci Lett 161:135–143

Ding ZL, Derbyshire E, Yang SL, Yu ZW, Xiong SF, Liu TS (2002a) Stacked 2.6-Ma grain size record from the Chinese loess based on five sections and correlation with the deep-sea $\delta^{18}O$ record. Paleoceanography 17:1033. doi:10.1029/2001PA000725

Ding ZL, Ranov V, Yang SL, Finaev A, Han JM, Wang GA (2002b) The loess record in southern Tajikistan and correlation with Chinese loess. Earth Planet Sci Lett 200:387–400

Dodonov AE (1991) Loess of Central Asia. GeoJournal 24:185–194

Dodonov AE (2007) Central Asia. In: Elias S (ed) The encyclopedia of Quaternary sciences. Elsevier, Amsterdam, pp 1418–1429

Dodonov AE, Baiguzina LL (1995) Loess stratigraphy of Central Asia: palaeoclimatic and palaeoenvironmental aspects. Quatern Sci Rev 14:707–720

Eden DN, Hammond AP (2003) Dust accumulation in the New Zealand region since the last glacial maximum. Quatern Sci Rev 22:2037–2052

Eitel B, Blumel WD, Huser K, Mauz B (2001) Dust and loessic alluvial deposits in Northwestern Namibia (Damaraland, Kaokoveld): sedimentology and palaeoclimatic evidence based on luminescence data. Quatern Int 76–77:57–65

Eitel B, Hecht S, Mächtle S, Schukraft G, Kadereit A, Wagner GA, Kromer B, Unkel I, Reindel M (2005) Geoarchaeological evidence from desert loess in the Nazca–Palpa region, southern Peru: palaeoenvironmental changes and their impact on pre-Columbian cultures. Archaeometry 47:137–158

Eitel B, Kadereit A, Blumel WD, Huser K, Lomax J, Hilgers A (2006) Environmental changes at the eastern Namib desert margin before and after the last glacial maximum: new evidence from fluvial deposits in the upper Hoanib river catchment, northwestern Namibia. Palaeogeogr Palaeoclimatol Palaeoecol 234:201–222

Enzel Y, Amit R, Crouvi O, Porat N (2010) Abrasion-derived sediments under intensified winds at the latest Pleistocene leading edge of the advancing Sinai-Negev erg. Quatern Res 74:121–131

Finaev A (1995) Processes of transportation and sedimentation of dust aerosol. In: Global analysis, interpretation, and modeling: first science conference, 25–29 Sept 1995, IGBP Secretariat of Germany in Berlin, Garmisch-Partenkirchen, p 22

Flint RF (1971) Glacial and Quaternary geology. Wiley, New York, 906 pp

Folguera A, Zárate M (2011) Neogene sedimentation in the foreland zone between 34°30´and 41°S and its relation to the Pampa Central block uplift and the tectonic Colorado basin. In: Salfity J, Marquillas R (eds) Cenozoic geology of central Andes of Argentina. Instituto del Cenozoico, Salta, pp 123–134

Frechen M, Kehl M, Rolf C, Sarvati R, Skowronek A (2009a) Loess chronology of the Caspian Lowland in northern Iran. Quatern Int 198:220–233

Frechen M, Seifert B, Sanabria JA, Argüello GL (2009b) Chronology of late Pleistocene Pampa loess from the Córdoba area in Argentina. J Quatern Sci 24:761–772

Gaiero DM (2007) Dust provenance in Antarctic ice during glacial periods: from where in southern South America? Geophys Res Lett 34, L17707

Gaiero DM, Simonella L, Gassó S, Gili S, Stein AF, Sosa P, Becchio R, Arce J, Marelli H (2013) Ground/satellite observations and atmospheric modeling of dust storms originating in the high Puna-Altiplano deserts (South America): implications for the interpretation of paleo-climatic archives. J Geophys Res Atmos 118:3817–3831

Goudie AS, Parker AG, Bull PA, White K, Al-Farraj A (2000) Desert loess in Ras Al Khaimah, United Arab Emirates. J Arid Environ 46:123–135

Grimley DA (2000) Glacial and nonglacial sediment contributions to Wisconsin episode loess in the central United States. Geol Soc Am Bull 112:1475–1495

Grolier MJ, Overstreet WC (1978) Geologic map of the Yemen Arab Republic (San'a'), United States Geological Survey, Miscellaneous Investigations Series, Map 1-1143-B, scale 1:500,000

Guo ZT, Ruddiman WF, Hao QZ, Wu HB, Qiao YS, Zhu RX, Peng SZ, Wei JJ, Yuan BY, Liu TS (2002) Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China. Nature 416:159–163

Haase D, Fink J, Haase G, Ruske R, Pésci M, Richter H, Altermann M, Jäger K-D (2007) Loess in Europe – its spatial distribution based on a European loess map, scale 1:2,500,000. Quatern Sci Rev 26:1301–1312

Haberlah D (2007) A call for Australian loess. Area 39:224–229

Hatté C, Antoine P, Fontugne M, Rousseau D-D, Tisnérat-Laborde N, Zöller L (1999) New chronology and organic matter $\delta^{13}C$ paleoclimatic significance of Nussloch loess sequence (Rhine Valley, Germany). Quatern Int 62:85–91

Hatté C, Gauthier C, Rousseau D-D, Antoine P, Fuchs M, Lagroix F et al (2013) Excursions to C4 vegetation recorded in the upper Pleistocene loess of Surduk (Northern Serbia): an organic isotope geochemistry study. Clim Past Discuss 9:187–215

Heller F, Liu TS (1982) Magnetostratigraphic dating of loess deposits in China. Nature 300:431–433

Hesse PP, McTainsh GH (2003) Australian dust deposits: modern processes and the Quaternary record. Quatern Sci Rev 22:2007–2035

Iriondo MH (1997) Models of deposition of loess and loessoids in the upper Quaternary of South America. J South Am Earth Sci 10:71–79

Johnsen SJ, Dahl-Jensen D, Gundestrup N, Steffensen JP, Clausen HB, Miller H, Masson-Delmotte V, Sveinbjörnsdottir AE, White J (2001) Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP. J Quatern Sci 16:299–307

Kehl M (2009) Quaternary climate change in Iran–the state of knowledge. Erdkunde 63:1–17

Kemp RA, Zárate MA (2000) Pliocene pedosedimentary cycles in the southern Pampas, Argentina. Sedimentology 47:3–14

Kemp RA, Toms PS, Sayago JM, Derbyshire E, King M, Wagoner L (2003) Micromorphology and OSL dating of the basal part of the loess-paleosol sequence at La Mesada in Tucumán. Quatern Int 106–107:111–117

Kemp RA, Zárate MA, Toms P, King M, Sanabria J, Arguello G (2006) Late Quaternary paleosols, stratigraphy and landscape evolution in the Northern Pampas, Argentina. Quatern Res 66:119–132

Kruck W, Helms F, Geyh M, Suriano J, Marengo H, Pereyra F (2011) Late Pleistocene-Holocene history of Chaco-Pampa sediments in Argentina and Paraguay. Quatern Sci J 60:188–202

Kukla G, An Z (1989) Loess stratigraphy in central China. Palaeogeogr Palaeoclimatol Palaeoecol 72:203–225

Lang A, Hatté C, Rousseau DD, Antoine P, Fontugne M, Zöller L et al (2003) High-resolution chronologies for loess: comparing AMS^{14}C and optical dating results. Quatern Sci Rev 22:953–959

Letolle R, Mainguet M (1993) Aral. Springer, Paris, 357 pp

Liu T (1985) Loess in China, 2nd edn. China Ocean Press/Springer, Beijing/Berlin, 224 pp

Livingstone I, Warren A (1996) Aeolian geomorphology. Addison Wesley Longman Limited, Essex, 211 p

Lü TY, Sun JM (2011) Luminescence sensitivities of quartz grains from eolian deposits in northern China and their implications for provenance. Quatern Res 76:181–189

Maher BA, Thompson R, Zhou LP (1994) Spatial and temporal reconstructions of changes in the Asian palaeomonsoon: a new mineral magnetic approach. Earth Planet Sci Lett 125:461–471

Markovic SB, Oches E, Sumegi P, Jovanovic M, Gaudenyi T (2006) An introduction to the middle and upper Pleistocene loess-paleosol sequence at Ruma brickyard, Vojvodina, Serbia. Quatern Int 149:80–86

Markovic SB, Hambach U, Catto N, Jovanovic M, Buggle B, Machalett B et al (2009) Middle and late Pleistocene loess sequences at Batajnica, Vojvodina, Serbia. Quatern Int 198:255–266

Marshall LG, Hoffstetter R, Pascual R (1983) Geochronology of the continental mammal-bearing tertiary of South America. Palaeovertebrata, Montpellier, Mém. Extr. 1–93

Matsu'ura T, Miyagi I, Furusawa A (2011) Late Quaternary cryptotephra detection and correlation in loess in northeastern Japan using cummingtonite geochemistry. Quatern Res 75:624–635

McCraw JD (1975) Quaternary airfall deposits of New Zealand. In: Suggate RP, Cresswell MM (eds) Quaternary studies, vol 13. Bulletin of Royal Society of New Zealand, Wellington, pp 35–44

McTainsh G (1984) The nature and origin of the aeolian mantles of central northern Nigeria. Geoderma 33:13–37

McTainsh G (1987) Desert loess in Northern Nigeria. Z Geomorphol NF 31:145–165

Molloy L (1998) Soils in the New Zealand landscape: the living mantle, 2nd edn. New Zealand Society of Soil Science, Lincoln University, Canterbury

Muhs DR (2007) Loess deposits, origins, and properties. In: Elias S (ed) The encyclopedia of Quaternary sciences. Elsevier, Amsterdam, pp 1405–1418

Muhs DR (2013a) The geologic records of dust in the Quaternary. Aeolian Res 9:3–48

Muhs DR (2013b) Loess and its geomorphic, stratigraphic, and paleoclimatic significance in the Quaternary. In: Shroder JF (Editor-in-chief), Lancaster N, Sherman DJ, Baas ACW (volume eds) Treatise on geomorphology, vol. 11, Aeolian geomorphology. Academic, San Diego, pp 149–183

Muhs DR, Bettis EA III (2003) Quaternary loess-paleosol sequences as examples of climate-driven sedimentary extremes. Geol Soc Am Spec Pap 370:53–74

Muhs DR, Ager TA, Bettis EA III, McGeehin J, Been JM, Begét JE, Pavich MJ, Stafford TW Jr, Pinney D (2003) Stratigraphy and paleoclimatic significance of late Quaternary loess-paleosol sequences of the last interglacial-glacial cycle in central Alaska. Quatern Sci Rev 22:1947–1986

Muhs DR, McGeehin JP, Beann J, Fisher E (2004) Holocene loess deposition and soil formation as competing processes, Matanuska Valley, southern Alaska. Quatern Res 61:265–276

Muhs DR, Bettis EA III, Aleinikoff J, McGeehin JP, Beann J, Skipp G, Marshall BD, Roberts HM, Johnson WC, Benton R (2008) Origin and paleoclimatic significance of late Quaternary loess in Nebraska: evidence from stratigraphy, chronology, sedimentology, and geochemistry. Geol Soc Am Bull 120:1378–1407

Nettleton WD, Chadwick OA (1996) Late Quaternary redeposited loess-soil developmental sequences, South Yemen. Geoderma 70:21–36

Péwé TL (1975) Quaternary geology of Alaska, U.S. Geological Survey Professional Paper 835. U.S. Government Printing Office, Washington, DC, pp 1–145

Porter SC (2001) Chinese loess record of monsoon climate during the last glacial-interglacial cycle. Earth Sci Rev 54:115–128

Porter SC, Hallet B, Wu X, An Z (2001) Dependence of near-surface magnetic susceptibility on dust accumulation rate and precipitation on the Chinese Loess Plateau. Quatern Res 55:271–283

Pye K (1995) The nature, origin and accumulation of loess. Quatern Sci Rev 14:653–657

Qiang XK, Li ZX, Powell CM, Zheng HB (2001) Magnetostratigraphic record of the Late Miocene onset of the East Asian monsoon, and Pliocene uplift of northern Tibet. Earth Planet Sci Lett 187:83–93

Qiang XK, An ZS, Song YG, Chang H, Sun YB, Liu WG, Ao H, Dong JB, Fu CF, Wu F, Lu FY, Cai YJ, Zhou WJ, Cao JJ, Xu XW, Ai L (2011) New aeolian red clay sequence on the western Chinese Loess Plateau linked to onset of Asian desertification about 25 Ma ago. Sci China 54:136–144

Rabassa J, Coronato A, Ponce JF, Schlieder G, Martínez O (2011) Depósitos glacigénicos (Cenozoico tardío-Cuaternario) y geoformas asociadas. Relatorio del XVIII Congreso Geológico Argentino, Neuquén, pp 295–314

Roberts HM, Muhs DR, Wintle AG, Duller GAT, Bettis EA III (2003) Unprecedented last glacial mass accumulation rates determined by luminescence dating of loess from western Nebraska. Quatern Res 59:411–419

Roberts HM, Muhs DR, Bettis EA III (2007) North America. In: Elias S (ed) The encyclopedia of Quaternary sciences. Elsevier, Amsterdam, pp 1456–1466

Rossignol J, Moine O, Rousseau D-D (2004) The Buzzard's Roost and Eustis mollusc sequences: comparison between the paleoenvironments of two sites in the Wisconsinan loess of Nebraska, USA. Boreas 33:145–154

Rousseau D-D (1991) Climatic transfer function from Quaternary molluscs in European loess deposits. Quatern Res 36:195–209

Rousseau D-D, Antoine P, Hatté C, Lang A, Zöller L, Fontugne M, Ben Othman D, Luck JM, Moine O, Labonne M, Bentaleb I, Jolly D (2002) Abrupt millennial climatic changes from Nussloch (Germany) Upper Weichselian eolian records during the last glaciation. Quatern Sci Rev 21:1577–1582

Rousseau D-D, Derbyshire E, Antoine P, Hatté C (2007a) Europe. In: Elias S (ed) The encyclopedia of Quaternary sciences. Elsevier, Amsterdam, pp 1440–1456

Rousseau D-D, Sima A, Antoine P, Hatte C, Lang A, Zöller L (2007b) Link between European and North Atlantic abrupt climate changes over the last glaciation. Geophys Res Lett 34, L22713. doi:10.1029/2007gl031716

Rousseau D-D, Antoine P, Gerasimenko N, Sima A, Fuchs M, Hatté C, Moine O, Zoeller L (2011) North Atlantic abrupt climatic events of the last glacial period recorded in Ukrainian loess deposits. Clim Past 7:221–234

Rozychi SZ (1991) Loess and loess-like deposits. The Publishing House of the Polish Academy of Science. Ossolineum, Wroclaw, 187 pp

Sarnthein M, Tetzlaff G, Koopmann B, Wolter K, Pflaumann U (1981) Glacial and interglacial wind regimes over the eastern subtropical Atlantic and North-West Africa. Nature 293:193–196

Schellenberger A, Veit H (2006) Pedostratigraphy and pedological and geochemical characterization of Las Carreras loess–paleosol sequence, Valle de Tafí, NW-Argentina. Quatern Sci Rev 25:811–831

Singer MJ, Verosub KL (2007) Mineral magnetic analysis. In: Elias S (ed) The encyclopedia of Quaternary sciences. Elsevier, Amsterdam, pp 2096–2102

Smalley IJ (1995) Making the material: the formation of silt-sized primary mineral particles for loess deposits. Quatern Sci Rev 14:645–651

Smith J, Vance D, Kemp R, Archer C, Toms P, King M, Zárate M (2003) Isotopic constraints on the source of Argentinian loess-with implications for atmospheric circulation and the provenance of Antarctic dust during recent glacial maxima. Earth Planet Sci Lett 6682:1–16

Stevens T, Thomas DSG, Armitage SJ, Lunn HR, Lu H (2007) Reinterpreting climate proxy records from late Quaternary Chinese loess: a detailed OSL investigation. Earth Sci Rev 80:111–136

Stokes S, Horrocks J (1998) A reconnaissance survey of the linear dunes and loess plains of northwestern Nigeria: granulometry and geochronology. In: Alsharhan AS, Glennie KW, Whittle GL, Kendall CGSC (eds) Quaternary deserts and climatic change. Balkema, Rotterdam, pp 165–174

Stuut J-BW, Prins MA, Schneider RR, Weltje GJ, Jansen JHF, Postma G (2002) A 300-kyr record of aridity and wind strength in southwestern Africa: inferences from grain-size distributions of sediments on Walvis Ridge, SE Atlantic. Mar Geol 180:221–233

Sun J (2002a) Source regions and formation of the loess sediments on the high mountain regions of northwestern China. Quatern Res 58:341–351

Sun J (2002b) Provenance of loess material and formation of loess deposits on the Chinese Loess Plateau. Earth Planet Sci Lett 203:845–859

Sun J (2005) Nd and Sr isotopic variations in Chinese eolian deposits during the past 8 Ma: implications for provenance change. Earth Planet Sci Lett 240:454–466

Sun J, Zhu X (2010) Temporal variations in Pb isotopes and trace element concentrations within Chinese eolian deposits during the past 8 Ma: Implications for provenance change. Earth Planet Sci Lett 290:438–447

Sun J, Zhang M, Liu T (2001) Spatial and temporal characteristics of dust storms in China and its surrounding regions, 1960–1999: relations to source area and climate. J Geophys Res 106:10325–10333

Sun J, Yie J, Wu WY, Ni XJ, Bi SD, Zhang ZQ, Liu WM, Meng J (2010) Late Oligocene-Miocene mid-latitude aridification and wind patterns in the Asian interior. Geology 38:515–518

Sun YB, Tada R, Chen J, Chen HZ, Toyoda S, Tani A, Isozaki Y, Nagashima K, Hasegawa H, Ji JF (2007) Distinguishing the sources of Asian dust based on electron spin resonance signal intensity and crystallinity of quartz. Atmos Environ 41:8537–8548

Teruggi ME (1957) The nature and origin of Argentine loess. J Sediment Petrol 27:322–332

Tripaldi A, Forman SL (2007) Geomorphology and chronology of late Quaternary dune fields of western Argentina. Palaeogeogr Palaeoclimatol Palaeoecol 251:300–320

Tripaldi A, Zárate MA, Brook GA (2011) Late Quaternary paleoenvironments and paleoclimatic conditions in the distal Andean piedmont, southern Mendoza, Argentina. Quatern Res 76:181–294

Tsoar H, Pye K (1987) Dust transport and the question of desert loess formation. Sedimentology 34:139–153

Velichko AA, Bogucki AB, Morozova TD, Udartsev VP, Khalcheva TA, Tsatskin AI (1984) Periglacial landscapes of the East European Plain. In: Velichko AA, Wright HE Jr, Barnosky CW (eds) Late Quaternary environments of the Soviet Union. University of Minnesota Press, Minneapolis, pp 94–118

Velichko AA, Morozova TD, Nechaev VP, Rutter NW, Dlusskii KG, Little EC, Catto NR, Semenov VV, Evans ME (2006) Loess/paleosol/cryogenic formation and structure near the northern limit of loess deposition, East European Plain, Russia. Quatern Int 152–153:14–30

Verosub KL, Fine P, Singer MJ, TenPas J (1993) Pedogenesis and paleoclimate: interpretation of the magnetic susceptibility record of Chinese loess-paleosol sequences. Geology 21:1011–1014

von Suchodoletz H, Kühn P, Hambach U, Dietze M, Zöller L, Faust D (2009) Loess-like and palaeosol sediments from Lanzarote (Canary Islands/Spain) – indicators of palaeoenvironmental change during the late Quaternary. Palaeogeogr Palaeoclimatol Palaeoecol 278:71–87

Watanuki T, Murray AS, Tsukamoto S (2005) Quartz and polymineral luminescence dating of Japanese loess over the last 0.6 Ma: comparison with an independent chronology. Earth Planet Sci Lett 240:774–789

Westgate JA, Stemper BA, Péwé TL (1990) A 3 m.y. record of Pliocene-Pleistocene loess in interior Alaska. Geology 18:858–861

Whalley WB, Marshall JR, Smith BJ (1982) Origin of desert loess from some experimental observations. Nature 300:433–435

White K, Livingstone I, Gurney S, Dearing J, Bateman M (2002) Post-processing of mineral mixture maps for mapping surficial materials: the example of the Matmata loess, southern Tunisia. Int J Remote Sens 23:3091–3106

Wilkinson TJ (1997) Holocene environments of the high plateau, Yemen: recent geoarchaeological investigations. Geoarchaeology 12:833–864

Wright JS (2001a) "Desert" loess versus "glacial" loess: quartz silt formation, source areas and sediment pathways in the formation of loess deposits. Geomorphology 36:231–256

Wright JS (2001b) Making loess-sized quartz silt: data from laboratory simulations and implications for sediment transport pathways and the formation of 'desert' loess deposits associated with the Sahara. Quatern Int 76–77:7–19

Yaalon DH, Dan J (1974) Accumulation and distribution of loess-derived deposits in the semi-desert and desert fringe areas of Israel. Z Geomorphol Supplementband 20:91–105

Yang SL, Ding ZL (2006) Winter–spring precipitation as the principal control on predominance of C3 plants in Central Asia over the past 1.77 Myr: evidence from $\delta^{13}C$ of loess organic matter in Tajikistan. Palaeogeogr Palaeoclimatol Palaeoecol 235:330–339

Yang SL, Ding F, Ding ZL (2006) Pleistocene chemical weathering history of Asian arid and semi-arid regions recorded in loess deposits of China and Tajikistan. Geochim Cosmochim Acta 70:1695–1709

Zárate MA (2003) Loess of southern South America. Quatern Sci Rev 22:1987–2006

Zárate MA (2007) South America. In: Elias S (ed) The encyclopedia of Quaternary sciences. Elsevier, Amsterdam, pp 1466–1479

Zárate M, Blasi A (1993) Late Pleistocene-Holocene eolian deposits of the southern Buenos Aires Province, Argentina: a preliminary model. Quatern Int 17:15–20

Zárate MA, Kemp R, Toms P (2009) Late Quaternary landscape reconstruction and geochronology in the northern Pampas of Buenos Aires province, Argentina. J South Am Earth Sci 27:88–99

Zinck JA, Sayago JM (2001) Climatic periodicity during the late Pleistocene from a loess-paleosol sequence in northwest Argentina. Quatern Int 78:11–16