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# Loess Records

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## Key Words:

*Loess, eolian geomorphology, wind, silt grain size, paleosol, Quaternary, stratigraphy, paleoclimate, glacial, interglacial*

## Key points/objectives box

- Definition of loess
- Description of the properties of loess
- Description of the formation of loess
- The importance of loess as a Quaternary dust archive for paleoclimatological reconstructions

## Abstract

Loess is an eolian deposit, composed mainly of silt grains, which can be identified in the field as a distinct sedimentary body. It covers a significant portion of the land surface of the Earth and is one of the most important terrestrial archives of long-term dust deposition. Loess appears on almost all continents, and ranges in thickness up to several hundred of meters. Most loess sequences include buried soils (paleosols), alternating with unaltered loess layers. As the formation of loess is controlled, at least partly, by climate, alternating loess deposits and buried soils hold valuable information of Quaternary climatic and environmental conditions, especially of past wind regimes.

## Introduction

Loess can be defined as sediment dominated by silt-sized (2-63  $\mu\text{m}$ ) particles that have been entrained, transported, and deposited by the wind, and is identifiable in the field as a distinct sedimentary body. Similar to sand dunes, loess is an eolian sediment, not a soil and not a rock. Loess occupies an intermediate position in a continuum of eolian sediments, composed mostly of silt grains that are smaller than windblown sand (63-2000  $\mu\text{m}$ ), but coarser than long-range-transported dust (typically <10  $\mu\text{m}$ , fine silt and clays) (Muhs et al., 2014). Thus, a shorter, alternative definition of loess can be 'coarse dust deposit'.

The formation of sediment from wind-blown coarse dust is mentioned by Chinese scholars as early as  $\sim$ 2000 years ago; in the scientific literature, Leonhard (1824) was the first to coin the term Loeß or Loesch (pronounced "loose") to describe the texture of the sediment he studied in Germany. Later Lyell (1833) made the term 'loess' globally popular through his book 'Principles of Geology' (Smalley et al., 2001). Different definitions of loess were given through time, partly depending on the researcher's background. We refer to Smalley et al. (2001) for a comprehensive overview of the fascinating history of the development of the scientific study of loess.

Loess covers a significant portion of the land surface of the Earth,  $\sim 8.6 \cdot 10^6$ , about 6.6% of the global land area (Figure 1) (Li et al., 2020). Thus, it is one of the most important terrestrial archives of long-term dust deposition. Loess appears on all continents except Antarctica – it covers vast areas in Asia, Europe, North America and South America and appears in a more scattered

distribution in Africa, the Middle East, Australia and New Zealand (see below). Loess mostly mantles pre-existing landforms, with the thickest accumulations, partly due to fluvial redistribution of the eolian sediment, in valleys and stable upland regions. The thickness of the loess is variable, ranging from a few tens of centimeters to ~500 meters, depending on several factors, such as the age of the deposit, distance from the source, and climate. Many loess deposits exhibit only subtle primary structures or are simply massive, with limited occurrence of bedding structures. One of the main characteristics of loess is the formation of vertical faces along river banks and road cuts. This strength is related to the inter-particle binding of the sediments by clays and/or carbonates.

Loess formation includes five main stages: 1) production of the silt grains, 2) emission (i.e., entrainment by wind), 3) transport, 4) deposition, and 5) accumulation, also termed as loessification (some studies include diagenetic changes, such as weak carbonate cementation, as part of loessification). As all of these stages are controlled, at least partly, by climate, it is clear why loess is considered one of the most important terrestrial Quaternary paleoclimate archives. An important common feature of loess sections is buried soils (paleosols), alternating with unaltered loess layers. The frequent occurrence of buried soils within the loess sections adds to the significance of loess as a paleoclimate archive as the soils usually represent periods of landscape stability when dust deposition rate decreased/ceased. In this section we focus on Quaternary loess; however, there are pre-Quaternary loess deposits that share the same paleoclimatological importance as the Quaternary loess. The main difference is the lithification of the loess into mudstone and siltstone. For further reading on Pre-Quaternary loess, see Soreghan et al. (2023).

## Particle size distribution of loess

Particle size, and especially particle size distribution (PSD), is one of the distinctive and key features of loess. Given loess is an eolian deposit entrained and transported by wind, the detailed PSD of loess, and its variation in space and time, holds valuable information regarding the sources of the grains and their transport mechanism. The general relationships between grain size and eolian transport mechanism, wind energy, and environmental conditions have been known since the middle of the 20<sup>th</sup> century (Bagnold, 1941; Tsoar and Pye, 1987). In the case of loess, the fine

sands and coarse silt grains originate from local sources and are transported by saltation or in near-surface suspension. Medium to coarse silt grains originate from proximal sources and are transported in low-suspension clouds often in cyclonic events. Fine to very fine silt and clay grains can originate from both distal and proximal sources; in the case of the former, these grains are usually transported over long distances (tens to thousands of kilometers) in high suspension (Tsoar and Pye, 1987; Vandenberghe, 2013). A good example of these relationships is the bi-modal PSD of many loess deposits worldwide, exhibiting a coarse silt – fine sand mode and a fine silt – clay mode (as in the Negev loess, see below). This kind of PSD is interpreted as representing two sources of grain population (proximal and distal), each transported under different transport mechanisms (short-term suspension and long-term suspension).

The interpretations of the transport and sources of dust particles within loess that are based on grain size data were limited to general perspectives in earlier studies due to technological constraints. Over the last 20-30 years, progress in methodological and technical aspects of grain size measurements and modeling has yielded a new and exciting era of utilizing PSD in loess research (Vandenberghe, 2013). These advances included: 1) the use of laser-diffraction to measure PSD instead of the traditional sieving and sedimentation techniques, yielding accurate high-resolution PSD data, and 2) the development of statistical techniques to separate different subpopulations in a PSD of the loess and to quantify both the modal size and proportion of each subpopulation (termed as End Member Modeling Analysis or EMMA) (e.g., Paterson and Heslop, 2015). Overall, the PSD of loess is an outstanding proxy for the reconstruction of eolian processes and climatic conditions, as demonstrated by hundreds of studies.

## The composition of loess

From a very general perspective, the mineralogy of loess is similar to the upper continental crustal source rocks, i.e., a felsic (granitic) composition. Thus, most loess deposits exhibit a considerable amount of quartz grains and to a lesser degree feldspar (plagioclase, K-feldspar), mica, calcite, and clay minerals (Muhs et al., 2014). Accordingly, the geochemistry of loess is rich with SiO<sub>2</sub>, which ranges from ~45% to 75%. In the Southern Hemisphere (South America, New Zealand), loess can also be composed of mafic minerals. On a regional scale, the composition of loess changes according to the specific sources (usually a mixture of sources), and the climate

conditions (current and past). The composition of loess is a strong tool for studying provenance, especially when geochemical analysis is carried out on specific grain size fractions that were identified using the measurement and modeling of the loess's PSD. Thus, each grain population within the loess can be characterized by its mineralogical, chemical and isotopic composition, and hence tied to the source of the dust and to a transport mode.

## The formation of loess

Out of the five stages of loess formation mentioned above, two stages, the first (silt production) and the last (loess accumulation or loessification), are still under ongoing debate in the scientific community. The generation of silt grains is closely related to the question of the loess source(s). The classic and traditional model of loess formation, developed during early scientific investigations of loess, proposes that silt-sized particles are produced mostly by glacial grinding of crystalline bedrock surfaces, deposited in till, reworked by fluvial processes as outwash, and finally entrained, transported, and deposited by wind, forming what is termed as "glacial loess" (Muhs et al., 2014) (Figure 2). Glaciers are efficient producers of silt and the close geographic association of loess with glacial terrain (i.e., in Europe and in North America; Figure 1) supports this model. However, during the 1960s, scientists began to question this uniform theory of loess formation, when loess was studied in detail in warm deserts where glaciers were not present during the Quaternary (Smalley and Vita-Finzi, 1968; Yaalon, 1969). The formation of these "desert loess" deposits is still under debate, as several non-glacial processes were suggested to generate silt grains in deserts, such as frost shattering, chemical weathering, salt weathering, fluvial comminution, and eolian abrasion (Figure 2) (see below). Recently, the debate has focused on the question of whether eolian abrasion of sand grains can explain the formation of desert loess. See the chapter "Formation of dust grains and dust emission processes" by M. Sweeney in this section for a detailed explanation of these issues.

Not all loess deposits fall neatly into the categories of "glacial" or "desert" loess. For example, Li et al. (2020) have emphasized the importance of high-altitude, non-glacial processes, to form what they call "mountain loess." In addition, an often-overlooked source of silt grains in loess is particle inheritance from sedimentary rocks, such as siltstones and shales (Aleinikoff et al., 2008). Inheritance of silt-sized particles from sedimentary rocks can take place in glacial,

mountain, or desert environments. Finally, the multiple pathways of loess particle origins are not mutually exclusive. Loess in many regions likely has origins from both glacial and non-glacial processes, as well as some silt-particle inheritance.

The last stage of loess formation is loessification. Loess is ‘not just the accumulation of dust’ (Pecsi, 1990). Loessification is the term that describes several pedogenic/diagenetic processes that turn the accumulated dust deposit into loess with its typical structure and appearance. These processes are not well understood and are the focus of current research (see Sprafke and Obreht, 2016).

## Stratigraphy of loess and paleosols

Buried soils (paleosols) are common in loess sequences and are one of the key features of loess archives. Thus, many authors use the term loess-paleosol sequence to describe the alternating sequence of unaltered loess units and buried soils. In places, buried soils are easily distinguished from unaltered loess layers, and can even be separated by a clear unconformity; however, in many loess-paleosol sequences, the distinction between unaltered loess and soil is not clear. Probably the most accurate approach to describe these alternations is a competition between dust accumulation and soil formation (McDonald and Busacca, 1990). When dust accumulation rates are high, pedogenic processes cannot keep up and relatively unaltered sediment accumulates. In contrast, when dust accumulation rates are low, soil-forming processes extend deeper into previously deposited loess. In many regions, especially for glacial loess, glacial periods are dominantly periods of loess accumulation whereas interglacial periods are dominantly periods of soil formation. Thus, this alternation has been generally correlated with the deep-sea oxygen isotope record of glacial/interglacial cycles (Kukla, 1977). In the sections below, we present examples of loess-paleosol sequences and interpretations in several regions of the world. For a comprehensive review of paleosols within loess sequences, see the chapter “Paleosols in loess deposits” by D. Muhs in this section.

## Loess as a climatic archive

As outlined above, loess-paleosol sequences are significant Quaternary climatological archives, and thus loess deposits are widely used to reconstruct past climatic and environmental

conditions. The main advantages of using loess for this purpose are: 1) loess is widespread, 2) loess is sensitive to climatological conditions, 3) most loess sequences also contain buried soils, and 4) loess is relatively easily dated using luminescence methods that estimate the burial age of the sediments (radiocarbon dating can be used if organic matter is found).

As all five stages of loess formation are, at least partly, controlled by climate, valuable paleoenvironmental information can be obtained from loess-paleosol sequences. Specifically, since loess is an eolian deposit, it holds direct evidence of wind strength, direction and atmospheric circulation patterns. Loess thickness, dust accumulation rate and grain size decrease away from the sources of the loess thus, these spatial patterns can yield important clues about the paleo-winds that deposited the loess. Other climatic data can also be inferred from loess-paleosol sequences, such as air temperature. This can be reconstructed, for example, through the identification of sedimentary deformations, and by using geochemical and isotopic proxies. Because of the nature of buried soils, their identification holds important qualitative climatic information. Several characteristics of the buried soils (i.e. weathering degree, depth of leaching), can be used to infer quantitative estimation of past climatic conditions, such as rainfall.

Remains of past fauna and flora can also shed light on past climates; for example, land snail shells are often preserved in loess, and they are abundant in loess deposits from China, Europe, and North America (Muhs et al., 2014). Most 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 (Muhs et al., 2014; Rousseau, 1987).

In the following sections, we provide more detailed examples of the reconstruction of Quaternary climatic conditions from loess-paleosol sequences in several world regions. For a comprehensive review of the paleoclimatic reconstruction of loess archives, see the chapter “Paleoclimatic information from loess archives” by J. Vandenberghe and Y. Enzel.

## Loess in Asia

Loess covers extensive regions in Asia, especially in the mid-latitude arid–semiarid zone (Figure 3). The most widespread loess deposits in Asia occur in China, covering about 440,000 km<sup>2</sup> (Liu, 1985), distributed between latitudes 34–45°N and longitudes 75–130°E (Fig. 1). The most



continuous and thickest loess is in central North China, where it forms the Chinese Loess Plateau (CLP) (Figure 3). On the CLP, loess can be hundreds of meters thick and contains tens of interbedded paleosols. Another notable feature of Chinese loess is the NW-SE zonal trend in decreasing particle size, changing from sandy loess to silty- and clay-loess (Liu, 1985); moreover, large areas of gobi (stony desert) and sandy desert occur in the upwind direction of the CLP. In Central Asia, loess deposits are adjacent to mountain regions and dominantly cover piedmonts and hills. In contrast to the CLP, loess in Central Asia accumulates mostly on the windward slopes of the Central Asian orogenic belt, where it can be found at elevations up to 2,500–3,000 m. 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 thick (Ding et al., 2002b). Loess is widely distributed in the northern part of Iran, where the west-east stretching Alborz Mountains act as the main barrier to trap eolian dust entrained from central Asia. In the Asian portion of Russia, loess is extensive in central Siberia, extending to the northeast area in Yakutia (Muhs, 2018).

Magnetostratigraphic studies indicate that loess deposition in the CLP began at ~2.6 Ma (Liu, 1985). This yellowish Quaternary loess deposit is underlain by older reddish eolian strata of what has been called “Red Clay.” Although two Red Clay sites from the western edge of the Loess Plateau have basal ages of 22 Ma (Guo et al., 2002), all the other numerous magnetostratigraphic chronology sites across a vast area of the Loess Plateau have a basal age of ~7 Ma. Sun et al. (2022) emphasize that although there are also several reports about sparsely distributed loess-like fine-grained deposits in marginal basins in the NE Tibetan Plateau with Paleogene basal ages (51 - 40 Ma) (e.g., Li et al., (2018)), the eolian origin of these red-clay loess-like deposits is largely dependent on the end-member analysis of the particle-size distribution of fluviolacustrine/floodplain/playa sequences rather than pure Red Clay strata, therefore their eolian origin needs to be further investigated.

In Central Asia, stratigraphic and chronological studies have previously shown that loess began to accumulate about 2.5–2.0 Ma ago, and the loess–paleosol sequences at different sites can be correlated with each other. At present, there is still no report of terrestrial dust deposits older than 2.5 Ma in Central Asia. In Iran, although most studies focused on the upper Pleistocene

loess record, Taheri et al. (2017) suggested that the oldest loess could be up to ~2.4 Ma.

Loess in Asia was long considered to be derived from deserts. In China, the traditional view has been that loess material was mainly blown from upwind deserts (Liu, 1985). However, later studies have shown that these deserts are actually dust- and silt-holding areas rather than predominantly producers of dust (Sun, 2002). Smalley and Vita-Finzi (1968) pointed out that there are no specific desert processes that could produce the vast amount of silt required to form a large downwind loess deposit. It is worth noting that a basic geographic feature of Asian loess is that it is mainly distributed around high mountain ranges (High Asia) (Figure 3). The important role of physical weathering of rocks in high mountains, as well as glacial processes, in producing silt-sized particles in eolian deposits has been well studied and reviewed (Sun et al., 2022), and the processes can well be explained by a conceptual model (Figure 4).

The most prominent mountain building during the Cenozoic era gave rise to the uplift of the Tibetan Plateau and the other related high mountains that form High Asia. The uplifted mountains had a huge impact on climate, and surface processes such as chemical weathering and erosion. They not only enhanced the rain-shadow effect (aridification) in the Asian interior but also greatly strengthened mountain erosion when the higher elevation triggered frost weathering as well as the growth of glaciers. The tremendous volume of eroded debris from High Asia was the fundamental material that formed the largest mid-latitude desert and loess in the Northern Hemisphere. The most prominent mountains in Asia are the Tibetan and the Central Asian Orogenic Belt (CAOB, the longest accretionary orogen on Earth) (Figure 5). Sun et al (2022) suggest that the reactivation of the CAOB and the NE Tibetan Plateau played an important role in the deposition of the eolian Red Clay in the latest Miocene-Pliocene through its control of the production of vast amounts of silt-sized debris created by frost weathering and of the transportation by the enhanced strength of the northwesterly wind systems (Fig. 3). Detrital zircon ages demonstrate that the source materials of the late Cenozoic Red Clay were mainly derived from a mixed provenance of enlarged alluvial fans coherently linked to the late Cenozoic uplift of the CAOB and the NE Tibetan Plateau. These relations provide the basis for understanding the connections between the deep Earth (lithosphere) and surface processes and their impact on the ecosystem in Asia.

Loess–paleosol sequences on the CLP have provided abundant information about regional and global climate changes during the Quaternary (Liu, 1985). The most important studies of the orbital-scale paleoclimatic record on the Loess Plateau were completed by Ding’s group (Ding et al., 2002a). Based on detailed pedostratigraphy and magnetostratigraphy of the Baoji section, thirty-seven pedostratigraphic units were identified, representing thirty-seven major cold-to-warm climatic cycles during the past 2.6 Ma (Ding et al., 2002a). Ding et al. (2002a) used particle size records to infer the Earth’s orbital scale variations, which were used to form a stacked loess grain size time series, termed the “Chiloparts” record. Comparison of the “Chiloparts” record with a composite marine  $\delta^{18}\text{O}$  record during the past 2.6 Ma (Figure 6) shows that for the past 1.8 Ma, the loess-paleosol record can be correlated almost cycle-by-cycle with the marine record. Several discrepancies in the climatic events between the two records have also been identified, implying that regional forcing mechanisms may also have played a part in the climatic evolution of the CLP.

For the Central Asia loess, the best long-term paleoclimatic record is the Chashmanigar loess section of southern Tajikistan (Ding et al., 2002b). This section is about 200 m thick and consists of alternating loess and paleosol layers with a basal age of about 1.77 Ma (Ding et al., 2002b), but the most recent work provides a basal age of 2.1 Ma (Parviz et al., 2020).

## Loess in Europe

European loess generally lies outside the limits of the last Fennoscandian and Alpine glaciations (Figure 7), with extensive mantles in southern Russia, northern Ukraine and Belarus in the east, northern France and southern England in the west, and the Po Basin of northern Italy in the south. In Europe, the multiple layers of loess deposits suggest a cyclic climatic pattern. These sequences show couplets of loess and soil, corresponding to global glacial-interglacial climate cycles. On average, these cycles last approximately 100,000 years in the Late Pleistocene. Certain regions in Europe exhibit a notable correlation between loess sequences and river terraces, enabling relative dating of the eolian deposits. Here are a few examples.

1. Western Europe, exemplified by the St. Pierre-lès-Elbeuf sequence in Normandy, showcases four cycles overlying a tufa layer with an age of approximately 400,000 years (Marine Isotope Stage [MIS] 11) capping a terrace of the Seine River (Lautridou et al., 1974).

2. The Somme valley displays overlapping loess and paleosol sequences over different river terraces. The oldest sandy loess, situated on a terrace dating back roughly 1 million years, was deposited before the Bruhnes-Matuyama magnetic reversal (Antoine et al., 2021)
3. In the Rhine valley, the Achenheim loess comprises five loess-paleosol couplets rich in terrestrial mollusks, and capping sandy material from the Rhine River and the Vosges mountains (Rousseau, 1987).
4. Central Europe's Krems and Red Hill sequences in the Czech Republic hold a notable climatic history, stretching back to the Bruhnes-Matuyama boundary around 750,000 years ago (Kukla, 1977).
5. The Stari Slankamen sequence in Serbia provides a record of the past one million years, establishing the base of a comprehensive Danube loess stratigraphy correlated with the Chinese record (Marković et al., 2015).

Each climatic cycle record commences with a forest soil B-horizon, transitioning to steppe soil in central and Eastern Europe, and humid forest soil in Western Europe. Slope deposits exhibit distinct layers. These retain a more comprehensive history of past environmental changes compared to plateau settings. These include a distinctive light-colored dust layer known as Marker silt (Rousseau et al., 2013), followed by a pellet sand layer with overlying loess-like deposits. These layers formed during periods of sparse vegetation and exhibit specific grain size characteristics. Several dust horizons, aligning with Kukla's Markers, correspond to short events lasting approximately 2,000 years on average (Figure 8). These events synchronize with shifts in the polar front over the North Atlantic and correlate with changes in European vegetation. The deposition of overlying loess-like layers appears to be linked to moisture supply from the North Atlantic. However, Marker silts do not exhibit a similar relationship. This decoupling in dust deposition modes during MIS 5 (130-74 kyr BP) implies a climatic mechanism connecting polar-air outbreaks to atmospheric circulation patterns favoring meridional flow (Rousseau et al., 2013). This soil complex succession is identified as PKIII and PKII in Eastern Europe or the St. Saufflieu complex in Western Europe, and is extensively documented in European deposits.

Within the main overlying loess deposits in Europe, various paleosols offer valuable insights into past environmental conditions and facilitate section-to-section correlations. The Nussloch reference loess site, situated on the bank of the Rhine River, stands as a key record of the Last Climate Cycle (LCC). Spanning the time period from 60,000 to 18,000 years ago, this site presents a distinct pattern of alternating preservation between paleosols or pedogenic layers (such as tundra gleys or lightly oxidized layers) and paleodust (loess) units (Rousseau et al., 2017). These alternating layers have been precisely dated using  $^{14}\text{C}$  dating of earthworm granules present in every pedogenic unit (Moine et al., 2017). They correspond on a one-to-one basis with Greenland Interstadials (GI - paleosol) and Stadials (GS - paleodust) identified in ice-cores (Figure 9). Each type of paleosol at Nussloch mirrors the duration of the corresponding GIs. For example, the longest interstadial within the 38,000 to 15,000-year period, GI 8 (known as Lohne Soil in Germany, Vitachev soil in Ukraine, St Acheul-Villers Adam soil complex in France, Surduk soil in Serbia, or the base of PKI in the Czech Republic), is represented in the Nussloch stratigraphy as a well-developed Arctic brown soil. Conversely, shorter GIs like GI 3 and 2, among others, correspond to tundra gley soils of varying thickness or weakly oxidized horizons displaying slightly increased organic contents.

Determining the duration of soil formation periods, particularly within interglacial soils where upper profiles are often eroded, poses significant challenges. Nevertheless, at the Nussloch site, the observed interstadial Arctic brown and tundra gley paleosols do not display signs of erosion at the outcrops. This absence of erosion permits the development of time frames for soil development, estimated at approximately 880 to 180 years for the oxidized and tundra gley paleosols, and 4,200 to 1,090 years for the Arctic brown soils (Rousseau et al., 2017). These estimates contribute to establishing the chronology of the deposition sequence. Moreover, the pattern of paleosol-loess-unit couplets at Nussloch is not unique; it is also observed in the neighboring Schwalbenberg sequence in the Rhein valley (Fischer et al., 2021). Similar successions, albeit with local and regional variations, have been noted extending from Western Europe eastward to Ukraine. This climate pattern, defined for the LCC, has also been identified within the previous climate cycle (MIS 7-6, 243-130 kyr BP) at the Harletz sequence in Bulgaria along the Danube River. This demonstrates that European loess deposits recorded the abrupt

climate variations occurring in the North Atlantic and Greenland at least during the past two climate cycles.

A recent innovative study of various LCC sequences, focusing on the eolian deposits between observed pedogenic units, revealed that the record of GS in European loess deposits encompasses not only the stratigraphic thickness of the eolian interval but also the overlying pedogenic unit, which developed downward into the upper part of the eolian unit. Consequently, the lower stratigraphic limit of the eolian units overlying the pedogenic unit corresponds to the resumption of dust sedimentation from the younger GS. This discovery fundamentally alters the definition of the chronology of the studied sequences and the associated deduced parameters. Studies on sedimentation and mass accumulation rates from European loess sequences indicate dustier conditions in Western Europe compared to Central and Eastern Europe during GS 4 and 3, corresponding to the Last Glacial Maximum. The study estimated and compared the bulk mass accumulation rate (MAR) for the last two Bond cycles (38.2-29 kyr BP and 29-23 kyr BP), showcasing the highest MARs in Western Europe (Figure 10). This finding challenges the assumption that the last stadial intervals of a Bond cycle, including a Heinrich Event (HE) corresponding to a major iceberg discharge to North Atlantic from Northern Hemisphere ice sheets, were consistently the dustiest periods in every studied Bond cycle. It supports previous modeling studies suggesting that Heinrich Stadials experienced less severe climatic conditions compared to other stages. Furthermore, the MAR estimates calculated for the last two Bond Cycles indicate higher atmospheric dust content in Europe than those observed in China during the Last Glacial Maximum (Rousseau et al., 2021).

With these results in hand, the question arises: how was this dust transported? Geochemical findings from European loess sequences, collected along a transect spanning 50°N from Brittany to Ukraine, coupled with dust emission simulations, have unveiled the geographical distribution of the most significant European dust sources during the period between 34,000 and 18,000 years ago. The study of bulk sediment reveals that the majority of European dust traveled within the atmospheric boundary layer, covering only a few hundred kilometers or less from its source before deposition. This type of short-distance transport has also been identified at lower

(Mediterranean) latitudes, in Pleistocene loess deposits in northern and central Italy (Pasquetti et al., 2023) and central Spain (Wolf et al., 2019). Regarding dust transport from European sources, recent geochemical analyses of dust deposited over Greenland have revealed the presence of North African dust and European loess fingerprints (Újvári et al., 2021). This challenges the long-standing paradigm that Chinese dust was the only supplier to Greenland during glacial periods. This discovery holds significant implications for our understanding of abrupt dust variations in Europe and Greenland, and provides valuable insights into the spatial and temporal dynamics of climate changes, particularly when considering the radiative impact of dust.

## Loess in 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). 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., 2018a; Péwé, 1975). There are also large tracts of loess in the Palouse area of eastern Washington and adjacent Oregon (Busacca et al., 2003) and the Snake River Plain and adjacent uplands of Idaho and parts of Wyoming (Pierce et al., 1982; Thorp and Smith, 1952). 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 (Figure 11).

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 some non-glacial contributions as well (Bettis et al., 2003; Muhs et al., 2018b). Thus, loess units represent glacial and stadial periods, and paleosols (buried soils) represent interglacial or interstadial periods (Figure 12). To a great extent, therefore, loess deposition in this part of North America is a "turn-on/turn-off" process that differs from the more complex pattern seen in China. In the Mississippi River basin, the three youngest loess units are the Loveland Loess (also called Loveland Silt) of penultimate glacial age, the Roxana Silt (loess) of early-last-glacial age, and Peoria Loess (also called Peoria Silt) of late-last-glacial age. Dating of Peoria Loess to the last

glacial period, from about 30 ka to 15 ka (in calibrated radiocarbon years), is based on studies conducted at dozens of sections (Bettis et al., 2003; Muhs et al., 2018b) and an example from Illinois, near the Mississippi River source area, typifies this chronology (Figure 13). At the base of this section, the Sangamon Geosol (paleosol) is developed in Loveland Loess and is overlain by the Farmdale Geosol (paleosol) developed in Roxana Silt (loess). The major part of the section, overlying the Farmdale Geosol, is Peoria Loess, which is more than 16 m thick. Peoria Loess in distal locations is less than a meter thick, but near source rivers can reach extraordinary thickness, up to ~40 m in some sections in western Iowa (Bettis et al., 2003). The extent of Peoria Loess in this region is estimated conservatively to be at least ~400,000 km<sup>2</sup>.

Although loess in the greater Mississippi River drainage basin is derived broadly from sediments of the Laurentide ice sheet, different glacial lobes, which eroded source sediment from different bedrock terrains, made time-varying contributions to loess through the last glacial period. As an example, the section illustrated in Figure 13 (simplified from Muhs et al. (2018b)) shows that the earliest Peoria Loess was derived from northwestern glacial lobes (low mica, low carbonates), the middle period was derived from northeastern glacial lobes (high mica, high carbonates), and the latest period was loess derived again from northwestern glacial lobes (low mica, low carbonates).

Farther west, in the Great Plains region, loess is extensive and likely covers at least 200,000 km<sup>2</sup> or more, with Peoria Loess thicknesses ranging from a meter or less to over 40 m. Aleinikoff et al. (2008) showed that sedimentary rock (volcaniclastic siltstone of Tertiary age) is the most important source of silt-sized particles in Peoria Loess of last-glacial age. Despite the different mode of origin of Great Plains loess, radiocarbon and luminescence ages indicate Peoria Loess in the Great Plains accumulated at about the same time as Peoria Loess farther east (Mason et al., 2008). Thus, even without glaciers, the Great Plains region experienced favorable conditions for loess accumulation during the last glacial period. Unlike the Mississippi River basin, however, the Great Plains region also has a younger, Holocene eolian unit called Bignell Loess. Bignell Loess is typically much thinner than Peoria Loess and has a more limited distribution compared to Peoria



Loess. Both radiocarbon and luminescence ages indicate that it was deposited after a period of soil formation (the Brady Paleosol) in Peoria Loess, after ~10 ka (Mason et al., 2008).

Loess deposits of the Snake River Plain in Idaho have not received as much attention as those in other regions, and they are generally thinner than elsewhere. Nevertheless, loess probably covers several thousand square kilometers in this region, with thicknesses ranging from less than a meter to at least ~12 m. Pierce et al. (1982) summarized the loess stratigraphy at numerous localities over an ~400-km-long transect from western Wyoming to central Idaho and informally designated the youngest two units as loess "A" and loess "B." The two loesses are separated by a well-developed paleosol. Based on degree of soil development and stratigraphic relations with K/Ar-dated lava flows and well-dated Lake Bonneville flood deposits, they suggested that loess A was deposited during the last glacial period and loess B during the penultimate glacial period. These interpretations are supported by the observation that Holocene basalts in this region lack a loess cover.

The loess deposits in the Columbia Plateau, or "Palouse" region 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 et al., 2003). Loess covers more than 50,000 km<sup>2</sup> of this region, with deposits ranging from a few meters to ~75 m thick. The loess deposits preserve many paleosols, reflecting periods of nondeposition and stability between times of more active loess deposition. The timing of the loess accumulation in the Palouse region of eastern Washington differs from that of other loess deposits of North America and, indeed, the world (Busacca et al., 2003). In this area, the principal source of the loess is believed to be flood sediments of proglacial Lake Missoula. This proglacial lake may have formed at least six times in the Pleistocene (Busacca et al., 2003). Flood sediments were exposed after dams of such proglacial lakes were breached. Thus, the production of the loess deposits is believed to peak late in the glacial cycle. Luminescence ages and dated tephras show that the latest two episodes of loess accumulation in the Palouse region were between ~60 ka and ~20 ka, for the "L2" loess, and after ~17 ka, for the "L1" loess (see summary in Busacca et al., 2003).

Loess is widely distributed in Alaska and adjacent unglaciated parts of Canada and is geographically the most extensive surficial deposit in the region (Figure 11). The spatial extent has not been measured precisely, but probably is on the order of  $\sim 200,000 \text{ km}^2$ . In central Alaska, the loess record may extend back through the entire Pleistocene. The thicknesses of the deposits range from a few centimeters in some areas to more than 60 m near Fairbanks (P  w  , 1975). Throughout Alaska, loess deposits are thickest near rivers, with thicknesses decreasing rapidly with distance away from the rivers and downwind of valley dust sources. The transport and accumulation 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 and on adjacent uplands. Although there is indirect evidence for last-glacial-aged loess in Alaska, there are surprisingly few ages that directly record eolian deposits of this age. In those localities where last-glacial-aged loess is found, geochemical data indicate multiple sources from mountain glaciers, with the possibility that local katabatic winds, as well as regional winds, played a role in eolian silt transport (Muhs et al., 2018a). Paleosols are common in central Alaskan loess, indicating that loess deposition here, like elsewhere, has been episodic.

## Loess in South America

South American loess covers large areas of the lowlands east of the central Andes ( $\sim 18^\circ$ - $38^\circ$  S) (Figure 14). The deposits extend across  $\sim 800,000$  to  $1,000,000 \text{ km}^2$  of the Chaco Plain of Argentina, Bolivia and Paraguay, the Pampean plain of central Argentina along with neighboring areas of Uruguay, and southern Brazil (Rio Grande do Sul). The Bolivian Chaco loess is a mantle that accumulated on megafans with extensive dune fields and sandy fluvial deposits.

Numerous areas of the Argentinean Chaco megafans are also covered by loess. In central Argentina, the eolian system is a continuum, consisting of dune fields in the Andean piedmont as well as in the western and central Pampas, grading to sand mantles, and finally to a loess belt in the eastern Pampas. Thick loess deposits ( $\sim 50 \text{ m}$ ) have accumulated in the sub-Andean mountain valleys of northwestern Argentina (Tucum  n, Catamarca provinces). Loess is also present in the highland plains of the C  rdoba ranges. It has also been reported in Tierra del Fuego and the

eastern Andean piedmont (36°-37°S). Additionally, Holocene loess has been reported from the Atacama Desert of Perú.

The loess stratigraphic record dates back to the Neogene (Late Miocene - Pliocene) represented by a sedimentary cover with an average thickness of ~200 m and capped by calcrete, extending across the southern and southwestern Pampas. In the eastern Pampas, Quaternary loess consists of up to ~40-50-m-thick sequences of primary loess and reworked loess deposits. The uppermost ~5-15 m of these deposits are usually exposed along river banks, sea-cliffs and in quarries (Figure 15). Pedogenic features are present throughout the sections, usually including both welded and discrete paleosols with pedogenic and groundwater carbonate accumulations. Bioturbation structures (paleocaves, paleoburrows) associated with extinct megafauna, including mammals (e.g., rodents), are common. The loess is either pollen-sterile or with very low pollen concentrations although other palynomorphs have been reported. In addition, phytoliths within the loess and soils provide evidence of past vegetation.

In early studies, the chronology of the loess was estimated on the basis of vertebrate fossils and later combined with paleomagnetism. The occurrence of primary impact volcanic glass layers in the Neogene and Quaternary loess as well as in loess-like sequences, yielded useful tephrochronological benchmarks for stratigraphic correlations as several glasses from primary impact layers were accurately dated using the  $^{40}\text{Ar}/^{39}\text{Ar}$  technique. However, additional analyses are required to interpret the numerical ages, including the geologic context, appropriate dating methods, and composition. Some of the glasses encapsulated and preserved floral material, including biological signatures and organics (Schultz et al., 2014). Recently, detrital zircon U-Pb ages have also been reported from the Neogene loess deposits (Stubbins et al., 2023).

In the past two decades, several luminescence dates (TL, OSL, IRSL) were obtained from the upper Quaternary loess sections in the Chaco-Pampean and the sub-Andean mountain valleys. Recently, other numerical OSL dates were reported (Coppo et al., 2022). The loess chronology, however, is still poorly constrained, as it is based on very few numerical ages and depends on numerous assumptions across a large areal distribution of sequences in a very

heterogeneous environment. As a result, more studies and controls by different methods are needed.

The sub-Andean mountain valley loess of Tucumán and the northern Pampas of Buenos Aires province (Argentina) provide long and quasi-continuous records that have permitted inferences of the environmental history during a substantial period of the middle and late Pleistocene (Heil et al., 2010). The accumulation of loess was widespread across various localities of the northern and southern Pampas between 30 ka and 10 ka. Significant eolian 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 Zárate, 2016). A major decrease in loess accumulation rate occurred during the Pleistocene–Holocene transition (12–9 ka) as manifested by the formation of modern soil A horizons in several areas of the eastern Pampas. Yet, while the Holocene is mostly characterized by soil formation in the eastern Pampas, some other western and southwestern settings document a short period of loess accumulation between ~5 - 4 ka.

The Pampean loess deposits are chiefly of volcanoclastic composition, with particles made up of volcanic lithic fragments (basaltic, andesitic, and rhyolitic rocks), volcanic glass shards, feldspar (mainly orthoclase), plagioclase (albite to labradorite); quartz content is lower than 20%. The mineralogical and geochemical composition of loess and reworked deposits 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. Secondary source areas are the Pampean ranges of Córdoba and San Luis, the Paraná River basin, the southern Buenos Aires ranges, the Paleozoic and Mesozoic rocks that crop out in the south-central Pampas, and likely the igneous and metamorphic rocks of southern Uruguay (Zárate, 2003). The Tucumán mountain loess is thought to be derived from the northwestern Argentinian/southern Bolivian Andes and the Altiplano. Mineralogical and geochemical studies have also been conducted to analyze the origin of the high arsenic and fluoride content of groundwaters in the Chaco-pampean loess deposits. Volcanic glass from the loess has been considered the primary source of high arsenic (As) content. Recent research suggests that depositional and post-depositional processes are both controlling

the distribution of As in groundwater within the loess and reworked loess deposits (Sosa et al., 2019).

The accumulation of loess has been explained through a combined mechanism of fluvial and eolian interactions from the Andes to the eastern lowlands. Sediment particles were deflated from the Andean piedmont megafans and transported eastward to the lowlands. A similar pattern is thought to have occurred during the accumulation of the Neogene loess that was derived from the late Miocene-Pliocene megafans of the northern Patagonian fluvial systems (Stubbins et al., 2023).

Southern South America has been proposed as the most likely source area of the dust found in Antarctic ice cores. Patagonia, the Chaco–Pampean region, and the previously subareally exposed continental shelf are the specific areas considered to be potential dust sources. Geochemical analysis of Quaternary deposited dust in the eastern Antarctic Plateau corroborates the inference that the dust originated from southern South America (Patagonia/Tierra del Fuego and southern Puna) and Australia (Coppo et al., 2022).

## Loess in Africa and the Middle East

As opposed to the extensive and thick loess in Asia, Europe, and North America, loess in Africa and the Middle East is patchy and relatively thin (Figure 16). Yet, these loess deposits are crucial for agriculture as they serve as the parent material for some of the most fertile soils in these regions. The loess deposits in Africa and the Middle East are true Quaternary desert loess as their formation processes in these regions cannot be related to glaciers.

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 semi-arid to sub-humid climate regions; (2) in most sites, loess covers an area of  $10^3$ - $10^4$  km<sup>2</sup> and are <20 m thick; (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 bi-modal; (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).

The best-studied desert loess in northern Africa is located on the carbonate-rich Matmata Plateau in southern Tunisia (Coude-Gausson et al., 1987; Dearing et al., 2001). The Tunisian loess covers an estimated area of ~4,000 km<sup>2</sup> and reaches thicknesses of up to 20 m. Based on radiocarbon ages, Coudé-Gausson 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.

The best-known loess in the Sahel of Africa is the informally named Zaria loess, located on the Kano plains in north-central Nigeria (McTainsh, 1984). This is probably one of the largest desert loess regions known in the world, covering an area of 41,000 km<sup>2</sup> and located today in a tropical climate zone. Loess PSD is mainly tri-modal, 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 regions suggest the presence of a non-continuous 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 (Figure 17).

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 (Brunotte et al., 2009; Eitel et al., 2001) (Figure 17). Based on 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 source of quartz silt in the loess could also be the nearby quartz-rich Kalahari Sands that lie only a few tens to hundreds of kilometers to the east and southeast of the loess region. 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). There is a good temporal correlation between the period of 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<sup>2</sup> (Figures 17, 18). 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 bi-modal (50-60 μm and 3-8 μm), with a general upward increase of 1) the coarse-to-fine mode ratio and 2) the value of the modes, in all sequences that have been studied (Crouvi et al., 2017) (Figure 18). Bulk mineralogy is quartz, calcite, phyllosilicates, and feldspars, whereas the coarse mode is composed mostly of quartz and feldspars; OSL ages suggest that the Late Pleistocene Negev loess started accumulating at 95 ka. Crouvi et al. (2017) suggested that the main source of the coarse silt grains in the loess is the adjacent sand dunes in western Negev and Sinai that advanced eastwards during the Late Pleistocene. Saharan dust contributed the fine silts and clays. These authors 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 (Figure 16), on the volcanic plateau of Sana (Nettleton and Chadwick, 1996), and the United Arab Emirates (Goudie et al., 2000).

Crouvi et al. (2010) suggested that for all reported loess in Africa and the Middle East, sand seas supplied the coarse silt for desert loess, based on the following observations: (1) all loess sites are spatially associated with adjacent sand seas (Figure 16) and are located only a few tens of kilometers from sand dunes, within the range for eolian 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 paleo-wind 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 towards the loess in a few sites; (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 be used to support or rebut different hypotheses for the generation of silt in deserts. Since sand dunes are generally composed of well-sorted sand grains, with limited amounts of coarse silt grains, this observation strengthens the hypothesis raised in the past that eolian abrasion of sand grains is one of the important mechanisms for generating silt grains in deserts (see Sweeney in this section). Given the absence of glacial activity near most low-latitude deserts, even during the Late Pleistocene, and the large sand seas there (Figure 16), it is reasonable to infer that spalling might be the dominant source of silt, at least locally.

## Loess in New Zealand and Australia

Both Australia and New Zealand have extensive loess deposits, but although geographically close, the two countries have a very different eolian contexts (Figure 19). As the driest inhabited continent, eolian processes dominate vast regions of inland Australia, resulting in extensive linear dunes and stony desert pavements (gibber plains), the latter of which preserves underlying (but poorly examined) dust sequences. Loess in Australia remains relatively under-explored and unconventional. Loess deposits were not typically referred to as loess in the older literature due to strict adherence to interpreted conventions of loess characteristics, i.e., the requirement to be silt dominated, and produced by glacial grinding, however within broader, and arguably more appropriate definitions, Australia contains abundant desert loess (Haberlah, 2007). The most extensive accumulation of loess occurs in the eastern riverine plain of the Murray-Darling Basin (MDB), a >1 million km<sup>2</sup> drainage basin in south-eastern Australia (Figure 19). Known as 'Parna', it is red in color and distinguished by its high clay content and subplasticity, characteristics which



led to idea that the clays were transported as silt-sized clay aggregates (Figure 20) (Hesse and McTainsh, 2003). The extent of Parna is relatively well mapped, covering an area of approximately 50,000 km<sup>2</sup>, with deposits ranging in thicknesses from 10 cm to 9 m (Butler and Hutton, 1956; Hesse and McTainsh, 2003). Although no detailed source fingerprinting has been undertaken, it is considered to be derived from the floodplains of the MDB to the west. The drier western parts the Riverine Plain lack loess, attributed to difficulties separating loess from fluvial deposits and a lack of trapping vegetation. At least four units of parna have been identified, however, they remain largely undated (Hesse and McTainsh, 2003). Loess is also found along the eastern highlands of New South Wales (NSW), within the inland ranges of South Australia (SA) and New South Wales (NSW), along the south coast of SA, the western plains of Victoria, and in Tasmania (Figure 19). However, these deposits are poorly studied (Hesse and McTainsh, 2003). In the highlands of south-eastern Australia, widespread primary and secondary loess is derived from the MDB, with primary deposits of 3 m thickness accumulating between ~50 ka and the Holocene (Hesse et al., 2003). In the Flinders Ranges, SA, loess dating from the Last Glacial Maximum (LGM) is exposed in partially excavated valley fill sequences up to 7 m thick. Comprised of fine silt laminations, these sequences are interpreted as a combination of primary and secondary loess deposition (Haberlah et al., 2010). Loess/cover sands or secondary loess deposits are widespread in Tasmania, occurring as typically <50 cm deposits, although units up to 7 m occur in some localities (McIntosh et al., 2021). Despite past glaciation, Tasmania has a paucity of loess compared to New Zealand, attributable to the predominance of 'hard' intrusive rocks (Dolerite), tectonic stability/low relief and more limited glaciation.

New Zealand represents a more conventional loess production setting. It hosts extensive fine grained sedimentary rocks, there has been significant (and ongoing) glaciation on the South Island and the islands are tectonically very active, resulting in high silt production and extensive loess formation. It is estimated that loess >1 m thickness covers 10% of New Zealand (~27,000 km<sup>2</sup>), with thin loess (<1 m)/loessial soils covering 60-70% of landscape (~160,800-187,600 km<sup>2</sup>) (Eden and Hammond, 2003; Schmidt et al., 2005). The thickest loess cover occurs on the drier eastern side of both Islands, but particularly the South Island (Figure 19), where 'mountain loess' deposits of up to 15 m have formed since 30-40 ka (Almond et al., 2007; Eden and Hammond, 2003).

Sourced from braided river systems, river terraces and glacial outwash plains, these deposits are largely considered to have formed during glacial intervals however, Holocene-present day loess can be found forming downwind of major braided rivers (Figure 21) (Eden and Hammond, 2003). Loess is also present on the South Island's west coast, a super humid environment experiencing rainfall of >5 m/year and a high number of rain days (Eger et al., 2012). The North Island largely lacked glaciation, but still has a broad cover of 'mountain loess' derived from the rivers draining the axial ranges (Figure 21). It also contains volcanic loess derived from the reworking of tephra. In the Wanganui Basin eleven loess units spanning the last 500 ka are preserved on an uplifted marine bench (Eden and Hammond, 2003), while in the lower North Island, four generations of loess, dating from the last glacial cycle, are preserved within a series of related river terraces, where the youngest terrace contains the most recent loess and the oldest terrace preserves the entire sequence (Formento-Trigilio et al., 2003). In North and South Island loess sections, tephra provide key chronostratigraphic markers, with the Kawakawa Tephra (c.25 ka), from the Taupo supervolcano, being the most notable (Eden and Hammond, 2003). However, the dating of loess by luminescence, especially South Island loess, remains problematic, (Almond et al., 2007).

## Summary

Loess is a terrestrial coarse dust deposit, composed mainly of silt grains, which can be identified in the field as a distinct sedimentary body. It covers a significant portion of the land surface of the Earth and is one of the most important terrestrial archives of long-term dust deposition, holding valuable information on Quaternary climatic and environmental conditions. Loess covers about 6.6% of the world's land area - it covers vast areas in Asia, Europe, North America, and South America and appears in a more scattered distribution in Africa, the Middle East, Australia, and New Zealand. It ranges in thickness up to several hundred meters and includes buried soils (paleosols) in most sequences, alternating with unaltered loess layers. The two main pathways of loess formation (i.e. silt grain generation) include the 'glacial loess' derived from glacially ground rock, and 'desert loess' derived from non-glacial processes of rock/grain breakup. In some cases, loess silt grains can be inherited from silt-sized sedimentary rocks. Loess has distinct advantages over other Quaternary sediments for documenting climate change in that it provides a direct record of atmospheric circulation and, depending on the age frame, can be dated directly by both

luminescence and radiocarbon methods. Unaltered loess units are often used to reconstruct paleowinds using spatial trends of thickness and particle size whereas the paleosols within the loess sequences mostly represent periods of little or no loess accumulation.

## Figure Captions

Figure 1. Global loess distribution and continuity (from Li et al., 2020).

Figure 2. The two main pathways of loess formation (from Bridges and Muhs, 2012).

Figure 3. Distribution of loess in Asia (from Muhs, 2018).

Figure 4. Source to sink conceptual model of loess formation in Central Asia (from Sun et al., 2022).

Figure 5. Maps show the coupling between tectonic evolution and eolian accumulation in Central Asia. The enlarged alluvia fans of the uplifted Central Asia Orogenic Belt (CAOB) and the NE Tibetan Plateau and the widespread accumulation of the eolian Red Clay in the Chinese Loess Plateau began at ~7 Ma (from Sun et al., 2022).

Figure 6. Correlation of the Chiloparts grain size record with a composite marine oxygen isotope record. The major loess-paleosol units and the marine oxygen isotope stages are labeled (from Ding et al., 2002a).

Figure 7. Map of the European loess deposits with indication of the depth of the last glacial maximum sea level low stand and of the expansion of the British and Fennoscandian ice sheets, and of the Alpine ice-cap. Modified from Rousseau et al., 2021

Figure 8. Continuous, quantitative characterization of the Dolni Vestonice (DV) soil complexes. On the left are OSL ages (mean  $\pm$  error) and the DV pedostratigraphy. In the middle panel, various parameters measured. On the right correlations with Greenland interstadials and marine isotope stratigraphy. Eolian events (MS and ES) are clearly individualized, as are chernozems (CHZ – IHS) and “Lehmbröckelsände” (LBS – or pellet sands). (from Rousseau et al., 2013).

Figure 9. Map of Western European loess deposits with the location of some of the main sequences and the reference series from Nussloch. Stratigraphy of Nussloch showing the alternation of paleosols in brown and grey and eolian units in yellow. Correlation with the NGRIP  $\delta^{18}\text{O}$  and dust records with the assignment of the paleosol units to the Greenland interstadials (GI). Modified from Rousseau et al., 2017.

Figure 10. Maximum and minimum mass accumulation rates ( $\text{g}/\text{m}^2/\text{yr}$ ) estimated from key European reference sequences along a 50°N transect “Bond Cycle A” (between GI4 and GS3,

i.e., 29 to 23 ka b2k) and “Bond Cycle B” (between GI8 to GS5, 38.2 to 29 ka b2k) (Modified from Rousseau et al., 2021).

Figure 11. Distribution of loess (brown color) in North America and the extent of ice sheets during the last glacial maximum (light purple color; approximate outer extent of ice marked by heavy gray line). Loess distribution and extent of ice sheets compiled from Muhs (2018) and sources therein. Red dots show localities referred to in the text or figures. DH, Dalton Highway, Alaska; BH, Bignell Hill, Nebraska; R, Rulo site, Washington; MS, Meeman-Shelby Forest State Park, Tennessee; M, Morrison, Illinois. Modified from Muhs (2018).

Figure 12. Gallery of loess exposures from North America: (a) Bignell Hill, Nebraska, central Great Plains; (b) Yukon-Tanana Upland, central Alaska, along the Dalton Highway; (c) Rulo site, Palouse loess region, eastern Washington; (d) Meeman-Shelby Forest State Park, Tennessee, lower Mississippi River valley. All photos by D.R. Muhs.

Figure 13. Example of changing loess sources during the last glacial period, from Morrison, Illinois, upper Mississippi River valley. Note that the term “Geosol” is the formal stratigraphic name for paleosols within the state of Illinois. Modified from Muhs et al. (2018b).

Figure 14. Loess distribution in southern South America (modified from Zárata, 2003).

Figure 15. Photo of a Pleistocene loess section (~16 m thick) at the Gorina quarry near La Plata, Buenos Aires province, Argentina. a) Sedimentological log, b) Inclination record, c) Age model. (from Heil et al., 2010).

Figure 16. Distribution of loess, sand dune and sandy soils (arenosols) in Africa and the Middle East (modified from Crouvi et al., 2010).

Figure 17. Field photos of several loess bodies in Africa and the Middle East. A) Loess overlying volcanic sands, Famara Beach area, Lanzarote, Canary Islands (photo by D. R. Muhs); B) Loess along the Kusieb River in Namibia, interbedded with lacustrine units - The Homeb loess (photo by O. Crouvi); C) Secondary fluvial loess in the Negev desert, Israel, located along the fluvial systems: The upper terraces of Wadi Besor (photo by O. Crouvi); D) Primary loess in the Negev desert, Israel, located along summits and ridges. The Mt. Harif sequence (photo by O. Crouvi).

Figure 18. A) Map of Israel and its surroundings, with the distribution of sand dunes (yellow with black dots) and loessial (orange) and sandy (yellow) soils in the Negev and Sinai deserts. Arrows represent the main direction of high speed wind. Points represent studies loess and soil sequences, with the value of the coarse silt mode for the period 40-10 ka; contours represent the interpolation of these values, showing a decrease trend away from the sand dunes. B) A topographic cross section from North Africa to Israel showing the main proximal and distal dust sources for the Negev loess. C) PSD characteristics for Ramat Beka primary loess sequence, Negev. All figures from Crouvi et al. (2017).

Figure 19. Loess cover in New Zealand and Australia. A) Approximate loess (parna) cover in Australia. Other locations where loess is found are indicated on the figure. B) Loess cover in New Zealand (from Eden and Hammond, 2003).

Figure 20. Parna loess deposits, near the township of Wagga Wagga, Riverine Plain, Murray-Darling Basin, Australia. A) Parna at Brucedale near Wagga Wagga, showing a modern soil overlying a redder parna unit. The buff colored parna in the base of the photo contains abundant pedogenic calcium carbonate, typical of parna. Note the tape measure is 1.10 m. B) Close-up of the wider profile shown in A) with the tape measure in the same location in both images. C) Overview of the covered landscape west of Brucedale. All photos by S. Marx.

Figure 21. Loess and dust on the east coast of New Zealand's South Island. A) The Dashing Rocks Formation; a 6-10 m coastal loess exposure sitting directly over basalt bedrock at Dashing Rocks, Timaru, South Canterbury. The section represents a key location in the history of loess science, namely in 1890 John Hardcastle first concluded that loess formation was related to climate based on his investigation of this section (Smalley et al., 2001). B-E) Loess adjacent to the Rakaia River, New Zealand's widest braided river, Canterbury Plains, South Island. B) An approximately 3 m thick loess section overlaying river gravels at Barnhill, approximately 22 m above the modern Rakaia riverbed. C) Loess of suspected late Holocene age at Barnhill. Note the tape measure is 1.78 m. D) Dust plumes entrained from the Rakaia River, December 2022, east of Rakaia township. E) Modern loess forming small dune-like hummocks around the base of young pine trees at Barnhill, approximately 22 m above the

modern riverbed. Note the arrow indicates an approximately 15 cm high hummock dune.  
All photos by S. Marx.

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