See also: **Loess Deposits, Origins and Properties**. **Loess Records**: Central Asia. **Paleoclimate Reconstruction**: Sub-Milankovitch (DO/Heinrich) Events. **Paleosols and Wind-Blown Sediments**: Nature of Paleosols; Mineral Magnetic Analysis.

References

An, Z., Kukla, G., Porter, S. C., and Xiao, J. (1991). Magnetic susceptibility evidence of monsoon variation on the Loess Plateau of central China during the last 130,000 years. *Quaternary Research* **36,** 29–36.

An, Z. S. (2000). The history and variability of the East Asian paleomonsoon climate. *Quaternary Science Reviews* **19,** 171–187.

An, Z. S., and Porter, S. C. (1997). Millennial-scale climatic oscillations during the last interglaciation in central China. *Geology* **25,** 603–606.

Derbyshire, E. (2001). Geological hazards in loess terrain, with particular reference to the loess regions of China. *Earth Science Reviews* **54,** 231–260.

Greenland Ice-Core Project (GRIP) Members (1993). Climate instability during the last interglacial period recorded in the GRIP ice core. *Nature* **364,** 203–207.

Guo, Z. T., Ruddiman, W. F., Hao, Q. Z., *et al.* (2002). Onset of Asian desertification by 22 myr ago inferred from loess deposits in China. *Nature* **416,** 159–163.

Hovan, S. A., Rea, D. K., Pisias, N. G., and Shackleton, N. J. (1989). A direct link between the China loess and marine δ^{18}O records: aeolian flux to the north Pacific. *Nature* **340,** 296–298.

Kukla, G. (1987). Loess stratigraphy in central China. *Quaternary Science Reviews* **6,** 191–219.

Liu, J. G., and Diamond, J. (2005). China's environment in a globalizing world. *Nature* **435,** 1179–1186.

Liu, T. S. (1985). *Loess and the Environment.* China Ocean Press, Beijing, China.

Martinson, D. G., Pisias, N. G., Hays, J. D., *et al.* (1987). Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. *Quaternary Research* **27,** 1–29.

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

Porter, S. C., and An, Z. S. (1995). Correlation between climate events in the North Atlantic and China during the last glaciation. *Nature* **375,** 305–308.

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

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

Rutter, N., Ding, Z., Evans, M. E., and Wang, Y. (1991). Magnetostratigraphy of the Baoji loess-paleosol section in the north-central China Loess Plateau. *Quaternary International* **7,** 1–22.

Sun, J. M. (2002). Provenance of loess material and formation of loess deposits on the Chinese Loess Plateau. *Earth and Planetary Science Letters* **203,** 845–859.

Sun, J. Z. (1988). Environmental geology in loess areas of China. *Environmental Geology and Water Science* **12,** 49–61.

Xiao, J. L., Inouchi, Y., Kumai, H., *et al.* (1997). Eolian quartz flux to Lake Biwa, central Japan over the past 145,000 years. *Quaternary Research* **48,** 48–57.

Europe

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Introduction

The loess of Europe makes up the western end of the most extensive and voluminous loess belt on Earth that stretches some 10,000 km eastward to China's Pacific coast. Owing to its eolian origin, loess occurs on the landscape as relatively thin drapes, a few meters thick, on mountain foot slopes and on river terraces. Loess from five to several tens of meters in thickness is mainly found in basins, major river valleys, and on plateaus and extensive plains, as shown in the influential map of loess distribution in Europe published by Grahmann (1932). European loess generally lies outside the limits of the last Fennoscandian and Alpine glaciations (**Fig. 1**), 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. Although loess is described as an eolian sediment in Chinese texts more than 2 kyr old, the process link between dust transport and loess deposits was not widely accepted in Europe until the German scientist Richtofen published his work on the Chinese loess, which he considered very similar to the loess of eastern Europe (Pye, 1995; von Richtofen, 1882). For a definition of loess, see Pye (1984) and *see* Loess Deposits, Origins and Properties.

The discovery and first scientific description of European loess is attributed to Karl Caesar von Leonhard, who, in ca. 1820, noted pale yellow, unstratified sediment, containing snail shells and fossil root channels, in the Neckar River Valley east of Heidelberg, Germany. He called it 'loess,' a local word used to indicate a yellow lime-rich soil (Smalley *et al.*, 2001). A number of years later, von Leonhard showed the loess outcrop to Charles Lyell who was so impressed that he included substantial text on loess in his 'Principles of Geology' (1833), which certainly led to increasing recognition of loess by the world's geologists.

Loess of Europe: The Material

Mineralogy of European Loess

The most common mineral in most European loess is quartz (ca. 40–80%), the principal ancillary minerals

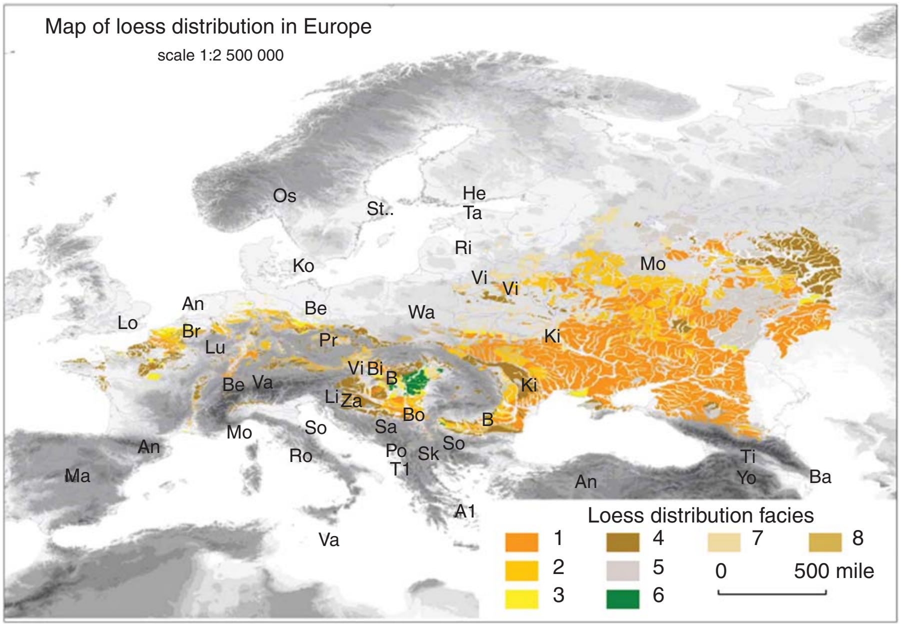


Figure 1 Loess distribution in Europe. Key to symbols: 1 – loess > 5 m; 2 – loess > 2 m; 3 – sandy loess; 4 – loess derivates; 5 – loess and loess derivates in fragmentary distribution; 6 – alluvial loess; 7 – eolian sands; 8 – loess thickness not differentiated. After Haase G, Haase D, Ruske R, Jäger KD, Altermann M, (2006). Loess in Europe – Spatial distribution in a scale 1 : 2,500 000. *Quaternary Science Reviews* (in press).

being the feldspars (predominantly K-feldspar), carbonates, and clay minerals. Exceptions include some Carpathian Basin loess, in which phyllosilicates are the dominant mineral group (up to 34%). Heavy minerals, although constituting only a small percentage (< 5%) by weight, have proved useful as indicators of provenance and degree of pedogenesis in both loess and paleosol units (Maruszczak and Wilgat, 1995). While the calcite–dolomite ratio is fairly consistent at about 3:1, carbonate content varies widely within Europe, for example, < 11% in Poland, 12–15% in The Netherlands, 5–20% in east Kent (UK), < 12% to >20% in northern France, and up to 25% at some sites in western Germany. Carbonate is present in both clastic and secondary forms, the latter occurring as concretions ('loess dolls'), pore linings, encrustations, and intergranular cements.

The finest fractions (clay grade: < 2 μm) of loess and paleosols are rich in clay minerals, and also include varying amounts of lithic and biogenic quartz. Kaolinite and illite are the most common clay minerals, together with chlorite, vermiculite, smectite, and several mixed-layer clays. Clay species vary regionally in response to source-area rock composition, sorting during transport, and postdepositional weathering. Smectite/illite is prominent in the loess of southern Poland (50–80% of the clay grade, the highest values occurring in the older units), with illite (up to 40%) and minor kaolinite (2–5% (Grabowska-Olszewska, 1988)). The smectite group (montmorillonite, nontronite, beidellite) is also prominent in loess and paleosols in parts of the Ukrainian plains, together with hydromicas, mixed-layer hydromica–montmorillonite minerals, kaolinite and halloysite. Ancillary minerals include chlorite, goethite, calcite, gypsum, and quartz (Perederij, 2001).

Morphology and Particle Size Distribution of European Loess

Although frequently described as a homogeneous sediment, the bulk properties of loess show important variations with age (i.e., the depth below the surface), location, site, source area, topography, and depositional and weathering history. For example, in regions such as Europe that were subjected to multiple glaciations in the Quaternary, glacial grinding produced abundant 'rock flour' that was deposited by meltwater, and reworked by the wind, as well as by periglacial braided fluvial systems such as the Danube, Dnieper, and Rhine rivers. The mainly mechanical breakage of rock particles into silt-sized (2–63 μm diameter) dust susceptible to deflation yielded particles that are dominantly of tabular and blade shape (Smalley, 1966). As most of these silt particles are transported in suspension, they lack the edge-rounding and 'frosted' surface texture so characteristic of wind-blown sand grains. Partly rounded particles in loess tend to be nonquartz components, including grains arising from certain secondary (chemical) postdepositional processes. The quartz grains in some of the loess in Normandy, France, and the Channel Islands are subangular in shape, but appear rounded because they are almost completely mantled in a clay coating rich in Si, Al, and Fe.

Sediments described as loess in Europe show a wide range of particle sizes. Leaving aside intraregional variations arising from distance from sources, silt content of loess by weight is generally between 60% and 80%, with $<20\%$ clay grade, and sand grades of $<15\%$ across a swathe of western European countries. In the loess of the Russian plain and Ukraine, the content of fine silt and clay ($<5\,\mu$m) in the south is approximately twice than that found further north, the particle size gradients being north–south in the west and northwest–southeast further to the east. Higher clay contents are general between the Volga and the Ural Mountains (Rozycki, 1991). A southeast-to-northwest particle size gradient, resulting from the northwestward advection of fine dust from the Caspian–Aral depression, is evident in southeast Europe; this transition zone runs northeastward from Bucharest, and marks the border between the Caspian–Black Sea loess zone and the western European loess supplied from dominantly Atlantic westerly (proglacial) and subsidiary southerly (Saharan) dust sources (**Fig. 2**; Rozyycki, 1991). Stratigraphically important volcanic tephras are present on both sides of this transition zone – the Eifel tephra, on the west side, indicating transport by the (south) westerlies, and those from the Caucasus carried by southeasterly winds. Other tephras have been identified in European loess series as, for example, the volcanic ash fallout of the Bag tephra in Hungarian loess during marine isotope stages (MISs) 10 and 8, and the tephra layer identified in the MIS3 loess in the Paks sequence (Frechen *et al.*, 1997; Horvath, 2001). More recently, in Germany, the loess sequences of the Rhine valley (Nussloch) have been shown to record the Etlviller tuff (Semmel, 1967) fallout during loess deposition in late MIS2 (Antoine *et al.*, 2001) contributing greater precision to the discussed age of this ash layer (Zöller *et al.*, 1988; Juvigné and Wintle, 1988).

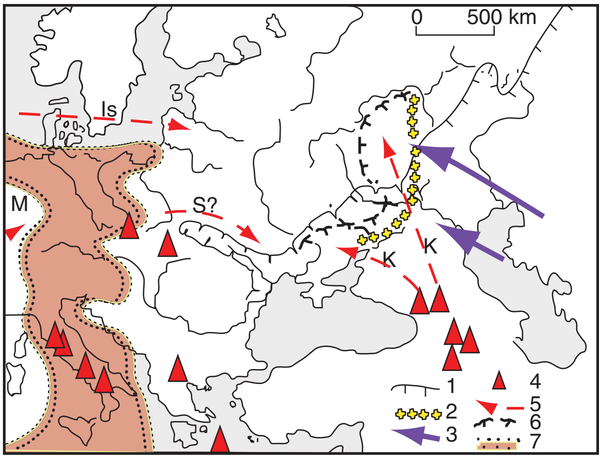


Figure 2 Reach of dust of various origins transported by long-distance eolian transport in eastern and central Europe. Key to symbols: 1 – Northwesterly extent of western Asiatic dust storms; 2 – border between Atlantic and western Asian systems; 3 – recorded transport paths of salts; 4 – volcanoes active in the Quaternary; 5 – volcanic dust pathways (K = north Caucasian; Is = Iceland; S = Sudetic (assumed); M = from Rhine maars); 6 – approximate extent of Caucasian volcanic ash; approximate margin of red dust precipitation from the northern Sahara. After Rozycki SZ, (1991). Loess and Loess-Like Deposits, p. 187. Wroclaw: Ossolineum-Polish Academy of Sciences.

The loess of western Europe varies with age and geographical location. Loosely packed coarse to medium angular silts, with little clay mineral content and limited, often localized cementation (comparable to much Asian loess), can be found at many sites in continental Europe. Thus, fabric varies with climatic type and variation through time, not only with changes between soil saturation and desiccation as well as the freeze-drying associated with cryoturbation (Van Vliet-Lanoë and Coutard, 1984), but with a suite of other processes including bioturbation, leaching and redeposition, snow meltwater infiltration, mineral weathering, natural loading and unloading, and reworking by running water and mass movements on slopes. Preferred fabric trends (anisotropic fabrics) are quite common in European loess. They range from visible lamination (as in alluvially redeposited loessic silts; Derbyshire and Mellors, 1988) to the strongly parallel particle fabrics generated *in situ* by cyclic freezing and thawing. *Limon à doublets* is a distinctive, non-calcareous loess facies found from the Channel Islands off the Normandy coast in the west to the Russian Plain in the east. Its distinctive fabric consists of thin, gently dipping alternating laminas of brown, clay-rich and gray, clay-poor layers, between 1 mm and >1 cm thick (Derbyshire *et al.*, 1988). The ‘doublets’ features are widely regarded as postsedimentary in origin, having been interpreted as thin layers enriched by pedological clay overprinted on previous grain size discontinuities, the concentration of clay and silt particles on lamellar freeze–thaw features having followed rapid decay of the permafrost at the end of the last glacial.

Calculation of mass accumulation rates (MARs) for loess of the last glacial period (~28–13 kyr BP) at over 30 sites across Europe (Frechen *et al.*, 2003) has indicated variable accumulation rates ranging from ~100 to 7,000 $\mathrm{g\,m^{-2}\,yr^{-1}}$ along an increasingly continental east–west transect. Making allowances for variation in regional and local silt sources as well as precipitation and wind patterns, which tend to result in the highest individual accumulation rates occurring on terraces of major rivers such as the

Rhine, a general pattern emerges in which the lowest mean rates occur on the northwestern periphery of Europe in France and Belgium (~100–600 g m^{-2} yr^{-1}), with higher accumulation rates evident toward the southeast, in the Czech Republic, Austria, and Hungary (800–3,200 g m^{-2} yr^{-1}).

Loess of Europe: The Origin

Atmospheric dynamics in Europe during the last glacial period were probably very different from those of today because of the presence of extensive and thick ice sheets. Thus, air masses were channeled into a west-to-east trending corridor along the 50° N parallel that broadly corresponds to the main loess-deposition belt in Europe. To the east of the Carpathians, in contrast, elevated terrain gives way to the western lowlands of Ukraine and Tajikistan. Here, reduced topographic constraints on airflow resulted in a mode of loess deposition quite different from that in the west.

Based on the comparison between the loess zones and mineralogical data (heavy minerals and silts), it is possible to locate the main source of Weichselian (last glacial age) loess in Europe. These studies show that loess in northwestern Europe originated from the North Sea, the central part of the English Channel, and Brittany (eastern English Channel, westward of the Cotentin peninsula). On the other hand, there were also local contributions, linked to the deflation of the main alluvial plains (Seine, Oise, Aisne, Marne, Somme), which were mixed with particles from the bedrock substratum (frost-shattered chalk, sand). There were also contributions from the dried-out and extended paleoestuaries of the Seine and Somme rivers, and from the wide alluvial braided floodplains of periglacial valleys.

According to Lautridou (1985), eolian deflation during the Weichselian should have prevailed in the large estuaries located 20–30 m below present sea level in the English Channel, which were partially preserved during the maximum lowering of sea level at the Last Glacial Maximum (LGM). In this context, loess sedimentation in northern France should have been supplied by deflation, which prevailed in the paleoestuary of the Somme River, and on the dense palaeochannel system of the eastern Channel (Auffret *et al.*, 1982; Antoine *et al.*, 2003a). In addition to these sources of loess, there were more local contributions, originating from the Oise, Marne, Meuse, or Rhine valleys. In Belgium, study of heavy minerals has shown that the main source of the Weichselian loess was the floor of the North Sea, which, at that time, consisted of sets of braided channels carrying the outwash of the Fennoscandian Ice sheet (Juvigné, 1985). Quite apart from any climatic factors, loess sedimentation in Europe was controlled by sources of available dust. Thus, the main zones of deflation identified in Europe are the dried-out plains (paleoestuaries) of the English Channel and the North Sea where it was exposed by sea-level lowering. Southward, the northern part of the Adriatic Sea at the mouth of the Po River played a similar role. Other sources include the alluvial plains occupied by braided channels during the Pleniglacial phases (times of maximum ice extent, roughly from 70 until 12 kyr BP) of the last glacial period. In these fluvial systems typical of periglacial environments, the numerous sandy bars, with sparse vegetation between channels, were probably subjected to intense eolian deflation. The Ukrainian loess, to the south of Kiev, probably originated in such a manner.

The European loess deposits occur as three main morphological types corresponding to the depositional environment and the presence of sedimentary traps.

(1) The platform loess, or ‘cover loess,’ in western Europe, occurs as a mantle of relatively constant thickness. This loess is a homogeneous facies, characterized by considerable spatial continuity, that corresponds to the coldest and driest phases of the upper Pleniglacial of the Weichselian ~30–15 kyr BP).

(2) Slope deposits – more localized, and of variable thickness – are preserved in sedimentary traps. This loess is deposited leeward of asymmetric valleys, features that occur frequently in Europe; loess deposition is influenced by a combination of valley orientation and wind direction. Dust accumulates on the leeward slope, where landform-induced turbulence allows dust to settle and where snow cover and local vegetation act as dust traps. In contrast, windward slopes are zones of deflation (nondeposition). Such phenomena also occur in a variety of local settings, including alluvial terraces and the acute slope angle between marine cliffs and fossil beaches, such as at Sangatte (northern France). The famous sequence at Red Hill near Brno shows the succession of several cycles of loess slope deposits linked to alluvial terraces. Kukla (1977) reviewed several such deposits in Europe.

(3) A third dune-like morphology, known as loess Greda, is linked to platform loess. Loess Greda look like elongated dunes several kilometers long; they have been described in central Europe by Léger (1990), and have also been observed on the right bank of the Rhine valley near Heidelberg (Antoine *et al.*, 2001). In the latter location, loess accumulation is mostly represented by upper Pleniglacial deposits (35–15 kyr), which reach a thickness of

15–20 m; Greda are oriented NNW–ESE, with small, discrete valleys between them.

Paleosols and Their Stratigraphic Significance in the Loess of Europe

The different loess units show a fundamentally cyclic climatic origin (Kukla, 1977). This cyclicity is expressed as an alternating series of loess and palaeosols that correspond to global glacial/interglacial climate cycles of 100-kyr average duration for the most recent ones (Kukla and Cilek, 1996). Every cycle has a forest soil B-horizon, which is overlain by a steppe (chernozem) soil in central and eastern Europe, and a humiferous forest soil in western Europe. In slope deposits, a light-colored dust layer overlies the black humiferous horizon abruptly; it is overlain by a pellet sand layer, which is capped by loess deposits. In 'platform' settings, this sequence is not so apparent; the slope deposits, which have preserved a much more complete record of past environmental changes, are more informative than those in platform settings. Platform deposits contain only direct airfall loess trapped by the local vegetation. Six stages in the development of soil complexes in loess have been summarized by Kukla and Koci (1972) (**Fig. 3**). The recognition of the different soils provides information on the paleoenvironmental conditions, and also provides a very useful tool for section-to-section correlation.

Many European loess studies have shown that abrupt changes in sedimentation are recorded in soil complexes as 'markers.' Markers are generally finer grained than normal loess but have no significant differences in composition (Hradilova and Stastny, 1994). An intriguing problem raised by markers is that of identification of the dust source which, given its fine grain size, may not have been close by (Rousseau *et al.*, 1998a). Markers may represent long-distance eolian transport because of their characteristic sharp contacts and much finer grain size. Thus, dust storms of continental magnitude seem to offer a possible explanation for the deposition of markers. Several studies report major dust events in historical time. Kukla (1977) reported that, on 5 April 1960, a storm deposited 3 cm of dust in Romania, carried from the Kalmyk steppe in Central Asia, for example, a distance of more than 2,000 km. Several dust storms have also transported red dust from the Sahara to Europe during the past 20–30 years.

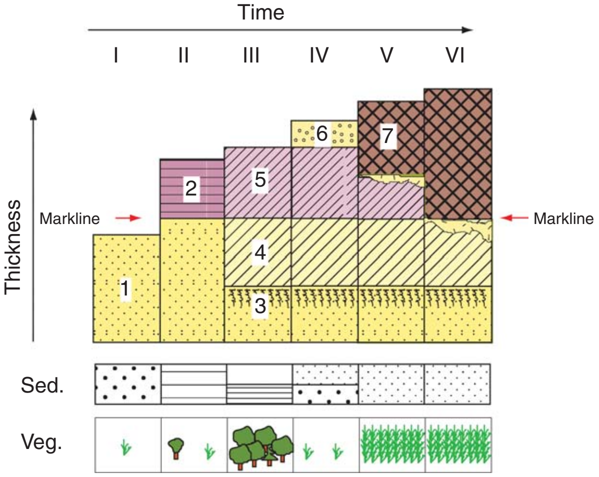


Figure 3 Schematic development of soil complex in loess areas. After Kukla G and Koci A, (1972). End of the Last Interglacial in the loess record. *Quaternary Research* 2: 374–383.

While loess sequences of the last climatic cycle are the best preserved in Europe, some loess–paleosol sequences show older cycles. In northwestern Europe, the St. Pierre-lès-Elbeuf sequence in Normandy shows four cycles (Lautridou, 1974), overlying a tufa with a mollusk fauna of probable MIS 11 (~400 ka) age (Rousseau *et al.*, 1992). The Somme valley shows overlapping loess and palaeosol sequences that overlie the different river terraces (Antoine, 1994). The oldest (sandy) loess, located on top of the terrace dated at about 1 Ma, was deposited at the end of the Lower Pleistocene before the B–M magnetic reversal (Antoine *et al.*, 2000, 2003b). The St. Vallier loess, near Lyon, is among the oldest in Europe, having been dated to 2.5–1.8 Ma by means of a tephra horizon of the Mont Dore volcanic system (Pastre *et al.*, 1996). In the Rhine valley, the Achenheim loess includes five loess–paleosol couplets, rich in terrestrial mollusks (Lautridou *et al.*, 1986; Sommé *et al.*, 1986). This sequence contains a yellow loess (the 'canary loess') that corresponds to MIS 12 (Rousseau, 1987a), and indicates particularly cold conditions. Finally, in central Europe, the Krems and Red Hill sequences (Czech Republic) are famous for the long climatic history they preserve, stretching back to the Bruhnes–Matyama boundary at about 0.75 Ma (Kukla, 1977). The loess sequence at Starnzendorf (Austria) records the Gauss–Matuyama paleomagnetic boundary at about 2.5 Ma (Kukla *et al.*, 1990).

Dating Loess in Europe: Geochronology

Most European last glacial loess chronology is based on luminescence dating methods, which include thermoluminescence (TL), optically stimulated luminescence (OSL), and infrared stimulated luminescence (IRSL) (Lang *et al.*, 2003; Wintle *et al.*, 1984; Zöller and Wagner, 1990). As the electron traps involved in these different solid-state physics processes appear to behave almost independently, several age determinations can be obtained from the same sample.

In Europe, the most common materials used for ^{14}C dating are charcoal and wood. These materials are uncommon in loess, and are rarely distributed in an order that provides a continuous, high-resolution chronology. A chronological framework was developed for the Nussloch loess sequence in Germany, based on AMS ^{14}C dating of loess organic matter (Hatté *et al.*, 2001b). The protocol used in this study is adapted to the particular characteristics of the Nussloch sequence (low organic carbon content, high carbonate content, and iron under +2 oxidation state (Hatté *et al.*, 2001a)). The resulting radiocarbon chronology is in excellent agreement with OSL ages, although the two chronological methods do not date identical events. Indeed, since luminescence techniques measure the time elapsed since the last sunlight bleaching event, and thus characterize pulses of dust, ^{14}C on loess organic matter determines the time elapsed since the death of the plant that grew and died on a loess surface before being covered by a new dust pulse. There is no notion of pulse for ^{14}C chronology since vegetation is always present. The general difference between luminescence and ^{14}C chronologies can be summarized by saying that the first characterizes a temporal framework in steps whereas the second smooths and somewhat leads the first one (Fig. 4).

Variability of Loess Sedimentation within a Single Glacial Period (Last Climatic Cycle) in Western Europe

Stratigraphic, paleopedologic, mollusk, and palynologic data, coupled with sedimentology, magnetic susceptibility, and TL/IRSL ages, provide a new

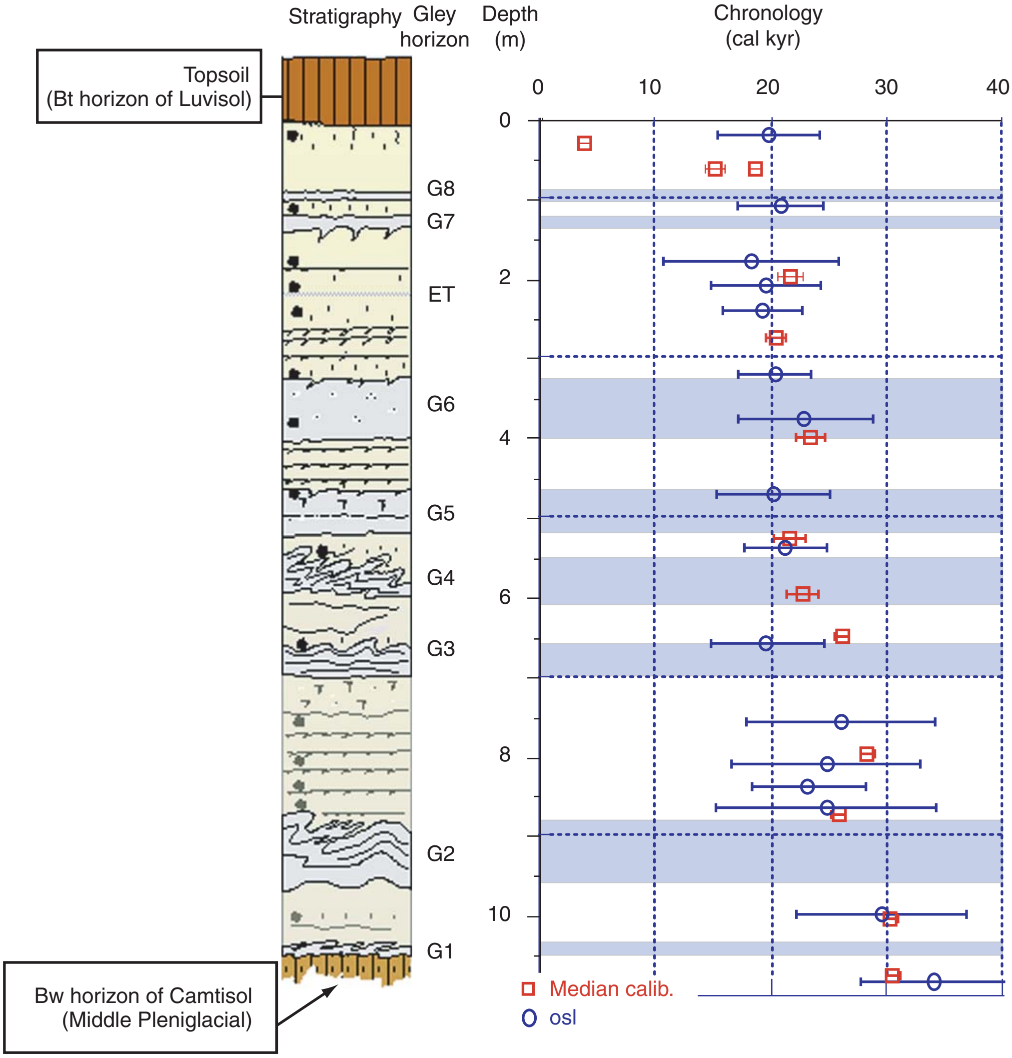
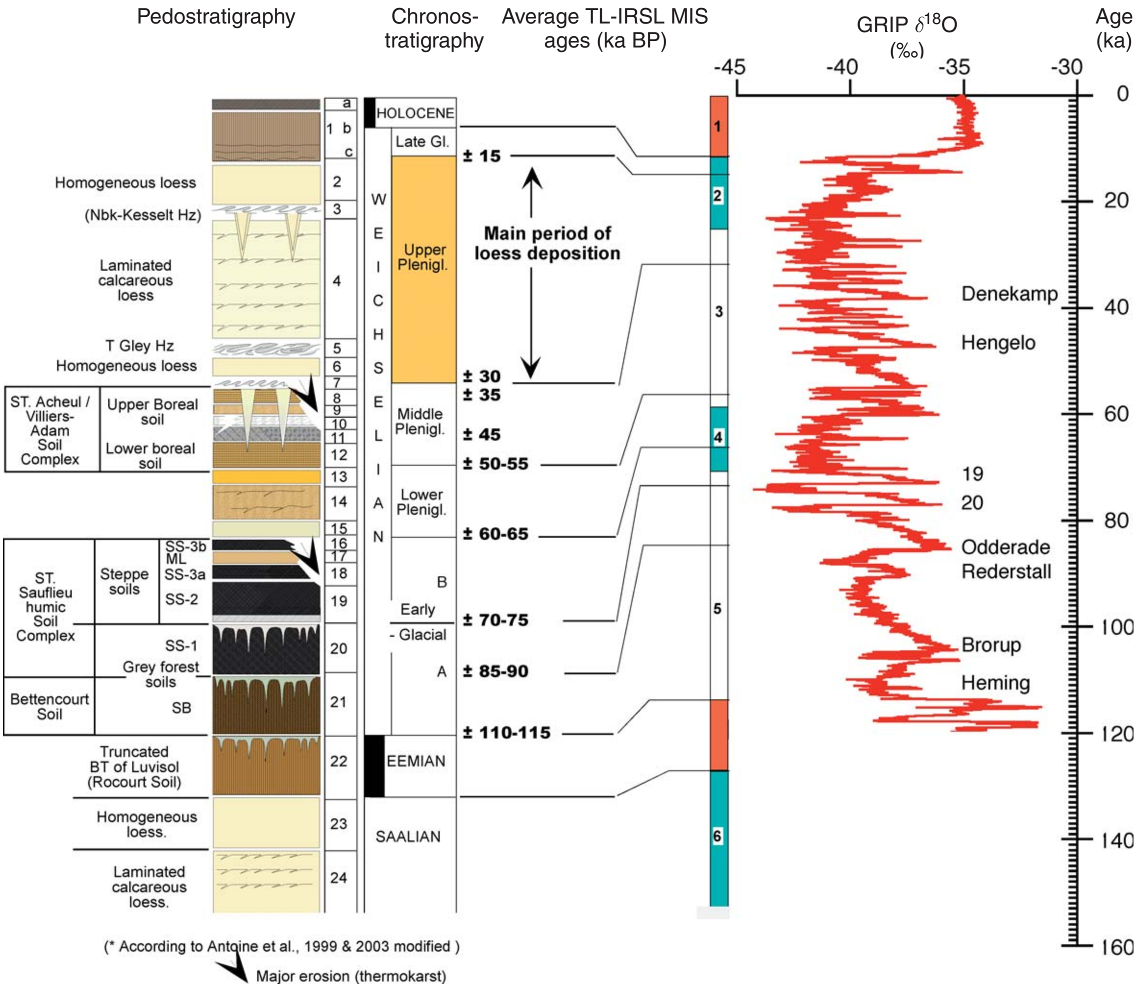


Figure 4 Comparison between the OSL and ^{14}C dates in the Upper Pleniglacial sequence of Nussloch. Key to symbols: G - Gley horizon; ET - Eltviller Tuff. Dates from Hatté *et al.*, 2001b; Lang *et al.*, 2003.



(* According to Antoine et al., 1999 & 2003 modified)

Major erosion (thermokarst)

Figure 5 Pedostratigraphy of the upper Pleistocene in western Europe. After Antoine P, Rousseau DD, Lautridou JP, Hatté C, (1999). Last interglacial–glacial climatic cycle in loess–paleosol successions of north-western France. *Boreas* 28: 551–563.

picture of the last climatic cycle in northwestern Europe, and its connection with neighboring regions (**Fig. 5**). The last interglacial period (including MIS 5e and part of MIS 5d (Kukla *et al.*, 1997)) in Europe is called the Eemian. After the truncation of the Bt horizon that formed in the Eemian paleosol (the Rocourt soil), the early Weichselian is represented by a complex of humiferous paleosols, known as the St. Saufflieu soils (Antoine *et al.*, 1994). This complex is characterized by the superimposition of a gray forest soil, locally doubled (Bettencourt-St. Ouen, Villiers Adam) and two or three steppe soils. The lower part, with its gray forest soils, correlates with the Brørup/Rederstall/Odderade succession (MIS 5d/5a) (**Fig. 6**). This sequence indicates a first continentalization of the environment, with development of gray forest soils in loess-derived colluvium, under a boreal forest of pine and beech (Munaut in Antoine *et al.* (1994), Antoine *et al.* (1999)). Above an erosional phase with evidence of deep seasonal frost (the end of MIS 5a), the upper part of the complex is characterized by soils that formed under some birch in a steppe environment with grass and aster family plants. This part of the pedocomplex probably represents the rapid climatic oscillations that prevailed during the transition between MIS 5 and 4 (interstadials 20 and 19 of the GRIP ice core record; Dansgaard *et al.* (1993)). The whole paleosol sequence shows an increasingly continental environment in two main phases, contemporaneous with sea level lowering (Sommé *et al.*, 1994). Thus, the paleogeographic change in the North Sea–Channel region contributed to the disappearance of the oceanic influence at the end of the last interglacial.

The upper boundary of the early glacial is defined by the erosive contact at the top of the last steppe soil (Antoine *et al.*, 1994). After the deposition of the first loess (the lower Pleniglacial), an extensive but short erosive episode is marked by laminated colluvium

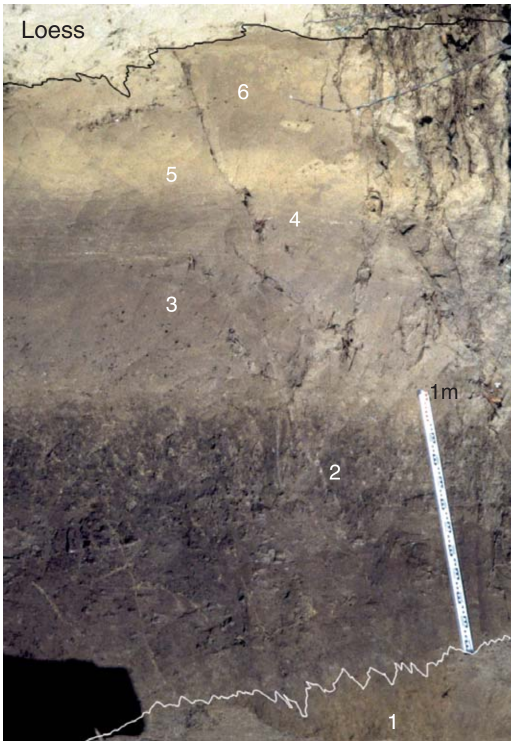


Figure 6 Paleosol complex of St. Saufflieu including the last interglacial paleosol and the humiferous soils of the early Pleniglacial. Photo by Pierre Antoine.

with soil fragments, cryoturbation, and frost cracks, which indicate frost reworking of the underlying levels. This unit, up to 2 m thick in northern France, is a marker level in the oldest part of the Weichselian. A similar record can be traced all the way to the Rhine valley (Antoine *et al.*, 2001; Haesaerts *et al.*, 2005).

The lower Pleniglacial loess is locally covered by younger loess, often heterogeneous and containing granules. Above this loess, a soil complex is found (Complex of St. Acheul-Villiers Adam) that corresponds to most of the middle Pleniglacial (MIS 3, 50–30 ka). During this period, loess sedimentation diminished and was interrupted by several phases of pedogenesis. These phases produced brown boreal soil to arctic brown soils. In most of the profiles in the Somme and Normandy, this period is represented by a unique polygenetic horizon (Saint-Acheul).

Elsewhere, in the sequences found in Villiers Adam, the loess is thicker (4 m) and contains four paleosols: a leached boreal soil, a humiferous arctic meadow soil (Van Vliet-Lanoë, 1987), a tundra gley, and an Arctic brown soil.

The lowermost part of the upper Pleniglacial loess marks the end of pedogenesis; it contains frost wedges and evidence of thermokarst (Antoine *et al.*, 2001). Following that, the main body of the upper Pleniglacial loess was deposited between ~25 and 15 ka. Typically, these deposits are about 4–5 m thick, but may locally reach 6–8 m in thickness. The upper Pleniglacial loess contains as many as three units, separated by periglacial palaeosol horizons (Antoine, 1991). The most common unit is the Nagelbeek/'Kesselt' tongue horizon, dated to about 22 ka ^{14}C yr (Haesaerts *et al.*, 1981). The modern soil is developed in the uppermost upper Pleniglacial loess. A high-resolution investigation in some western European loess has documented climate variability through different indices (biological, sedimentological, geochemical, and geophysical). The results show that during the last climatic cycle, the main loess deposition interval started at ~70 ka and ended at ~16–15 ka (Rousseau *et al.*, 1998b). Two main phases of loess deposition, centered around 60 ± 5 and 23 ± 8 kyr BP, are separated by a period with much lower sedimentation rates of between ±55 and 35 ka (Antoine *et al.*, 1999, 2001).

A similar sequence, with local variations due to the more continental conditions inferred from their geographical location, is available for central Europe (Kukla, 1977) (**Fig. 7**). A brown forest Bt soil at the base corresponds to the last interglacial. It is overlain by a biogenic steppe soil of chernozem type, interrupted by a Marker I, 2–10-cm thick. This is a sharply

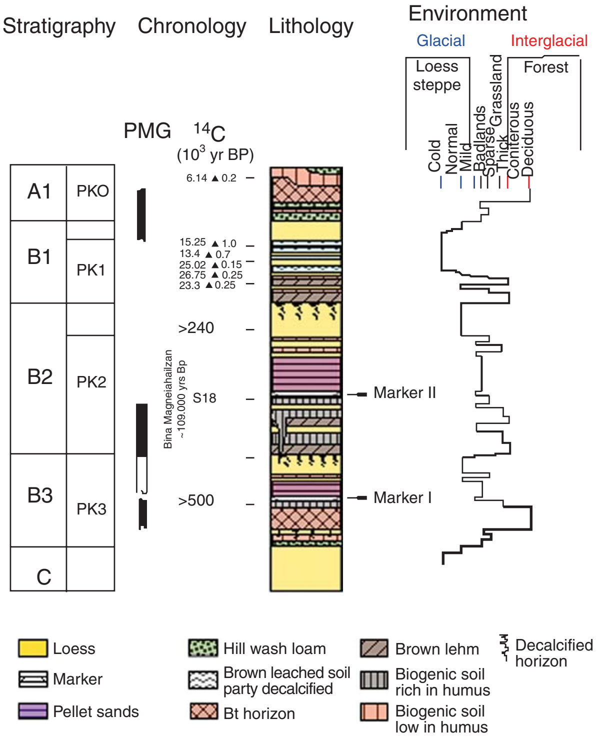


Figure 7 Pedostratigraphy of eastern Europe. After Kukla G, (1977). Pleistocene land-sea correlations. 1: Europe. Earth-Science Reviews 13: 307–374; Rousseau DD, (2001). Loess biostratigraphy: New advances and approaches in mollusk studies. *Earth-Science Reviews* **54**(1–3), 157–171.

delimited band of light-colored dust. It separates the underlying chernozem from the overlying hillwash loam composed of sand-sized fragments known as pellet sands. Fine loess caps this first pedocomplex (PKIII). This first eolian deposit is succeeded by a second pedocomplex (PKII) with a pseudogley overlain by a chernozem interrupted in some rare places by a new Marker horizon (IIa), immediately followed by small pellet sands capped by another loess. This succession is repeated a second time with a thicker chernozem interrupted by Marker II, overlain, in turn, by thick pellet sands and a loess with an age placing it at the base of MIS 4. A third soil complex developed after this lower Pleniglacial loess; it consists of a brown decalcified soil overlain by a thin loess, then a humiferous chernozem. This is pedocomplex PKI. Finally, the upper Pleniglacial displays the thickest loess deposits, with intercalated gley horizons, as observed in western Europe. A similar pattern, with regional differentiation, has also been described in the Ukrainian loess deposits near Lubny (Rousseau *et al.*, 2001). At Lubny, the loesses and paleosols correlate closely with those of central (Kukla, 1977) and western Europe. Thus, there is a remarkable consistency in the history of the last climatic cycle as recorded in the loess sequences of western, central, and eastern Europe over a distance of 2,500 km, as shown by Haesaerts *et al.* (2003, 2005). The differences observed relate to local conditions arising from the proximity of the Fennoscandian ice sheet and Alpine glaciers, or the influence of the westerlies and climatic variations over the North Atlantic.

Paleoclimatic Proxies in European Loess

The past few decades have seen the development of new paleoclimatic proxies, allowing a more precise interpretation of the European loess sequences. These include loess and paleosol geochemistry, identification of periglacial features, molluskan paleozoogeography, magnetic susceptibility, and detailed sedimentology.

Geochemistry

Few organic geochemistry investigations are available for European loess, but several recent studies of loess have been completed in France (Hatté, 2000; Hatté *et al.*, 1998) and Germany (Hatté *et al.*, 1999, 1998, 2001b; Hatté and Guiot, 2005; Pustovoytov and Terhorst, 2004). Other investigations are in progress in eastern Europe. Organic geochemistry studies are based on the 'fingerprint' of environmental conditions provided by plant δ^{13}C, and on its undisturbed conservation during burial and subsequent sedimentation. During photosynthesis, plants discriminate against ^{13}C because of differences in chemical and physical properties due to its greater mass (O'Leary, 1981). Both major types of photosynthetic pathways have a characteristic isotopic signature. C4 plants living in rather severe climatic conditions, with high insolation and/or water stress, show a mean δ^{13}C of -13 ± 2‰, whereas C3 plants, which prefer more temperate environments, present δ^{13}C values around -26 ± 4‰ (O'Leary, 1988). Variability around the mean δ^{13}C values in leaves of terrestrial vegetation (foliar δ^{13}C) results from environmental changes that influence stomatal conductance (e.g., Feng and Epstein (1995)). These results show that variation of the δ^{13}C in C3 plants within the range −30‰ to −22‰ is primarily influenced by the δ^{13}C, the concentration of atmospheric CO_2, and by precipitation, and, second, by soil type and texture and insolation. Temperature influence differs from one biome (association of plants) to another, but remains the most important parameter in the definition of the biome itself. On the other hand, variations of isotopic signature in C4 plants within the −15‰ to −11‰ interval must be almost exclusively linked to variations in the δ^{13}C in atmospheric CO_2. All these metabolic responses to environmental changes indicate that carbon isotopic composition of plants reflects climatic variations.

In contrast to interglacial soils, typical loess is associated with sparse vegetation and a weak rhizosphere. The absence of well-established pedogenesis and the dry glacial environment favor the degradation of organic matter without distortion of the isotopic signal, making typical loess suitable for an organic geochemical study. When properly prepared (Hatté and Gauthier, 2006), the carbon isotopic composition of loess organic matter is a powerful paleoclimatic indicator, because it inherits the δ^{13}C of growing plants that trap dust at the time of deposition. As environmental conditions and vegetation types (C3 vs. C4 photosynthetic pathways) control the δ^{13}C levels in plants, the δ^{13}C values of organic matter in loess can be used to infer temporal variations in climate and vegetation. Thus, the isotopic signal cannot be interpreted solely in terms of change in the ratio of C3 to C4 plants. Indeed, considering only the C3 photosynthetic pathway, δ^{13}C variations can be linked to first order changes in atmospheric CO_2 (δ^{13}C and concentration) and precipitation and, at the second order, to temperature, soil type and texture, and insolation.

In the Rhine Valley (Achenheim, France, and Nussloch, Germany), Hatté *et al.* (1998) demonstrated, with values ranging from −23‰ to −26‰, C3 origin of organic matter during the last glacial period (70 to 12 kyr BP), whereas Pustovoytov and Terhorst (2004) exhibited some C4 carbon-enriched

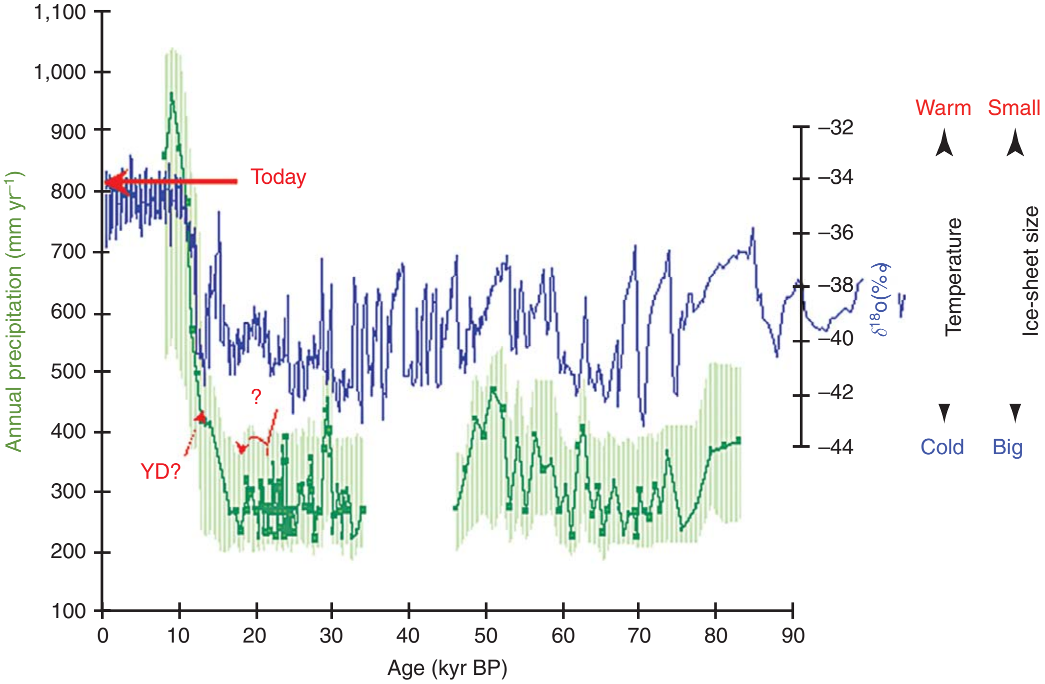


Figure 8 Reconstruction of annual precipitation in the Nussloch sequence. After Hatté C, Guiot J, (2005). Paleoprecipitation reconstruction by inverse modelling using the isotopic signal of loess organic matter: Application to the Nussloch loess sequence (Rhine Valley, Germany). *Climate Dynamics* **25**: 315–327.

layers (δ^{13}C from −16‰ to −19‰) within the same period in Schattenhausen, less than 1 km to the east of Nussloch. This conflict of view remains to be resolved, but two interpretations can be proposed. One concerns complications arising from carbonates in the loess. Another possibility is that there existed a mosaic of vegetation types, such as a mixture of C4 grasses and C3 trees.

Considering the C3 photosynthetic pathway only, Hatté *et al.* (1999, 1998) interpreted the variations in the δ^{13}C of loess organic matter in Nussloch (Germany, Rhine Valley) and Achenheim (France, Rhine Valley) as a response to changes in paleoprecipitation during the last glaciation. Using a linear relation between loess δ^{13}C and atmospheric CO_2 concentration and δ^{13}C, on the one hand, and precipitation on the other, Hatté *et al.* (2001a) attempted a deconvolution of the loess δ^{13}C record to reconstruct paleoprecipitation. However, paleoclimatic inferences were limited because only parameters of the first order were taken into account. Nevertheless, use of a vegetation model (Biome4) provides the required greater complexity by considering first- and second-order parameters. Inverse modeling of loess δ^{13}C in Nussloch provided reconstructed paleoprecipitation values that varied between 240 and 400 mm yr^{-1} through the last glaciation (Hatté and Guiot, 2005). This clearly demonstrated atmospheric teleconnections with the Greenland ice sheet extension, by matching Dansgaard–Oeschger (D/O) events with a precipitation increase of ca. 100–200 mm yr^{-1} (Hatté and Guiot, 2005) (**Fig. 8**).

Cryoturbation and Evidence of Ice Wedges

Cryoturbation features and ice-wedge casts occur at different stratigraphic levels in the northwestern European loess sequences, and represent marker horizons that allow correlation of sections (Lautridou and Sommé, 1974). Following the studies of Pissart (1987) and Van Vliet-Lanoë (1987), cryoturbation features are interpreted as the result of differential expansion of different surface materials in response to freezing. Indeed, in contrasting materials (e.g., loam vs. sand), the experiments performed in Caen indicate clearly the establishment of structures with a drop or pear shape when the pressure generated by this process is blocked at the surface by refreezing. In poorly drained environments with a surface water sheet, the cryogenic expansion, blocked by surface freezing, causes downward deformation. Conversely, in a well-drained environment, the cryogenic expansion can exert a force toward the surface, and so produce certain relief forms (tundra ostioles, soils with ice mounds).

Ice-wedge casts are produced from cracks caused by thermal contraction. They form progressively in a series of events, as follows: (1) cracking of the permafrost by thermal contraction in winter and (2) infilling

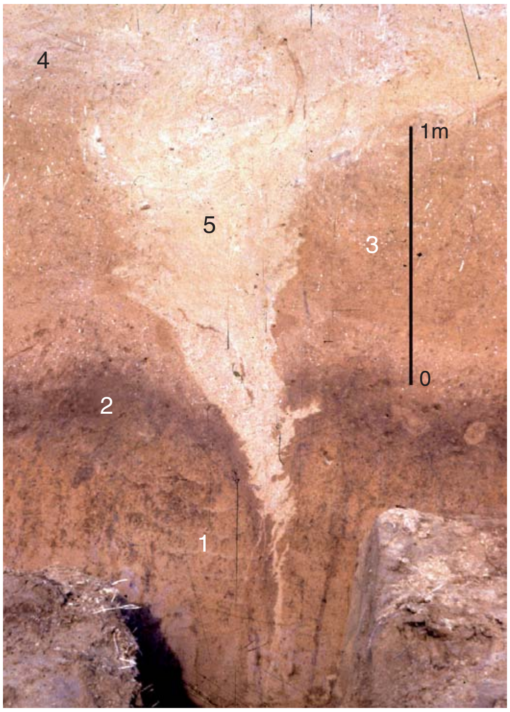


Figure 9 Ice wedge in the loess sequence at Sourdon. Photo by Pierre Antoine.

of cracks with meltwater produced by thawing of snow in spring, followed by refreezing (French, 1996; Péwé, 1962). The development of these structures indicates the occurrence of permafrost, with a mean atmospheric temperature lower than −8 °C, and lack of a thick snow cover. After the degradation of the ice wedge, the structure is often fossilized by loess sedimentation. The ice-wedge casts can be as large as 1 m wide and 2 m deep in the loess of northern France and Belgium (**Fig. 9**). In plan view, ice-wedge casts make up a network of polygons ±10–12 m wide. Their presence in the loess indicates significantly colder temperatures during the last glacial period.

Terrestrial Mollusks and Paleozoogeography

Terrestrial mollusk (gastropod) assemblages are one of the most powerful paleoclimate proxies in carbonate loess sequences (**Fig. 10**). Quaternary mollusk species are extant and do not show any changes in their ecological requirements. As the identification of the species is performed by considering the shell shape and ornamentation, it is then possible to use the present ecological requirements and zoogeography of living individuals to interpret the fossil assemblages. Variations in the specific composition of gastropods can be used to characterize past environments, and to reconstruct ecological and climatic parameters. Mollusk communities, including forest species, mainly represent temperate assemblages regardless of the region under consideration. Interstadial assemblages include species indicating cool and open conditions, whereas two main assemblages represent cold environments (Lozek, 1990; Rousseau, 1987b, 2001; Rousseau and Puisségur, 1990). One group best characterizes steppe environments and is dominated by four species of *Pupilla*. The coldest and wettest conditions of a tundra-like environment are represented by the *Columella* group, which includes more species than the *Pupilla* group. While climatic variations can be interpreted from multivariate analysis of the mollusk assemblages, the compilation of the assemblages over a large area also yields other important information. Indeed, the impoverishment of the mollusk assemblages in the western European Upper Pleistocene loess sequence has been interpreted as a response to the coldest and wettest condition that prevailed in this area. In contrast, conditions notably less maritime (Atlantic) characterized central Europe during the last glacial period, where the assemblages were both more abundant and more diverse (Rousseau, 2001; Rousseau *et al*., 1990). Transfer functions of terrestrial mollusks, following the modern analog principle, have been developed for European loess sequences, which show similar temperature reconstructions to those computed from pollen counts (Rousseau, 1991).

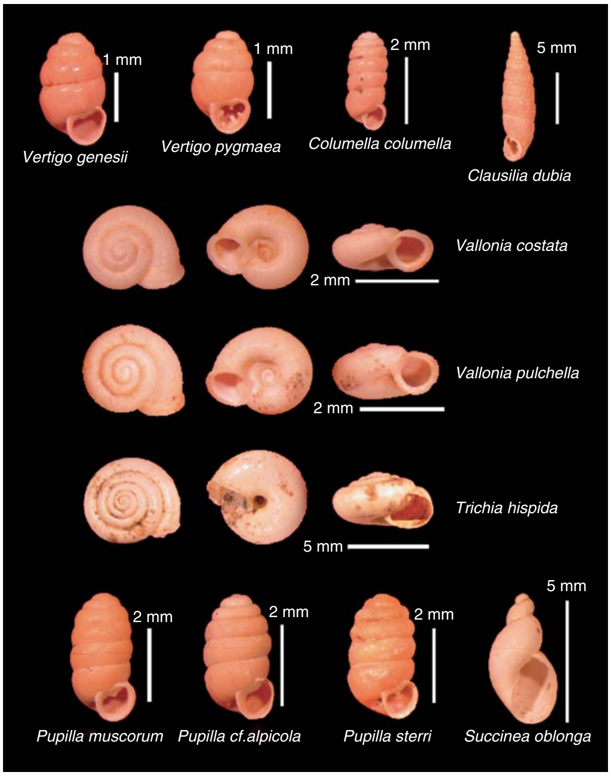


Figure 10 Main terrestrial mollusk species described from loess deposits. Photos by O. Moine.

Other methods have also been developed using the present distribution of the species, as well as the 'climate mutual range' method originally developed for beetles (Moine *et al.*, 2002). Finally, studies of Hungarian mollusk assemblages have used the ecological ranges of the observed species, applying a method similar to the one developed for micromammal studies by Okhr (Sümegi and Hertelendi, 1998). Terrestrial mollusks have also been studied for their amino acid signatures, which show significant differences from one climatic cycle to another (Oches and McCoy, 1995).

Sedimentology and Grain Size

The particle size distribution of loess is often used to determine variations in the composition of the sediment. However, variation in the different grain size classes can also be used to determine the relative wind velocity at the time of particle transport. Comparison of the different grain size classes, from silt to coarse sands, is widely used in loess studies. Shi *et al.* (2003) interpreted an increase in the coarser grain size fractions at Dolni Vestonice (Czech Republic) as corresponding to the record of the major iceberg discharges in the North Atlantic, called Heinrich Events. However, another approach is to define a grain size index, which corresponds to a ratio of two main particle size classes. Higher values indicate stronger winds. Two main indices have been developed. Studying the loess sequence at Kesselt in Belgium, Vandenberghe *et al.* (1998) defined the 'U ratio' as the ratio between the two size classes 16–44 and 5.5–16 μm. Similarly, in studying other European loess sequences, Antoine *et al.* (2002) developed the IGR index ratio defined as the ratio between coarse loam (20–50 μm) and fine loam and clay ($<20\,\mu$m), which is similar to the 'U ratio.' The IGR index can be used not only to reconstruct the wind dynamics but also as a new tool for the detailed correlation of different sequences within a limited area or along a transect. Results of studies using this method indicate that similar patterns can be traced from west to east right across Europe from northern France to Ukraine.

European Loess as a Record of the Response of the Continental Environments to North Atlantic Climatic Variability

Loess sedimentation in Europe appears to be rhythmic. Compared to Chinese loess, the European loess sequences (and especially those in western Europe) show a more discontinuous and contrasting record. These characteristics are linked to the influence of the North Atlantic Ocean that gives rise to more humid environments (increase in soil development, and periglacial structures) and to high-frequency (millennial) variations in loess depositional rates.

According to new studies, the loess of Europe records rapid climatic events similar to those described in the Greenland GISP2 and GRIP ice cores (D/O), and in marine cores from the North Atlantic (Bond cycles). The latest results (Hatté *et al.*, 2001b; Lang *et al.*, 2003) obtained in studies of the Nussloch loess sequence (Germany) indicate good correspondence between European loess and North Atlantic climate variability (Antoine *et al.*, 2001, 2002; Rousseau *et al.*, 2002) (**Figs. 11** and **12**).

The cornerstone hypothesis of the study of the Nussloch sequence in the Rhine Valley is that loess sedimentation, if it has global significance, should be coherent with the dust record preserved in Greenland ice. High-resolution analyses of the Nussloch loess sequence can best be compared to the Greenland dust record because both provide a record of Northern Hemisphere eolian dynamics. Both GRIP and GISP2 dust records show alternating phases of high or very low dust concentrations in the atmosphere, the latter corresponding to the D/O interstadial (IS) events (IS 2–24 of Dansgaard *et al.* (1993), being warm climatic intervals during which very little dust reached Greenland).

Measurements of magnetic susceptibility and pedostratigraphy show clearly that the succession of loess and palaeosols at Nussloch matches the general stratigraphy of the last climatic cycle in western Europe. This succession, dated by AMS radiocarbon and OSL, has been correlated with the GRIP dust concentration for the last climatic cycle (**Fig. 11**). Numerous events in the Greenland record corresponding to D/O events also appear to be recorded in the loess sequence (**Fig. 10**).

At Nussloch, the variations of the IGR index through time appear similar to the fluctuations in Greenland dust fluctuation during the 32–19 ka interval, where the temporal resolution is best (**Fig. 11**). Furthermore, similar and synchronous variations have been determined in other western European sequences (Achenheim, Mainz-Weisenau) within the EOLE project (CNRS-ECLIPSE program), providing support for the global value of the IGR grain size index used. Thus, it appears that the western European loess sequences faithfully record D/O events, with the Nussloch section rightfully considered as a key reference locality (Antoine *et al.*, 2002; Rousseau *et al.*, 2002). However, this record of the D/O events is a function of the strength and duration of interstadial warming, as is also expressed in the

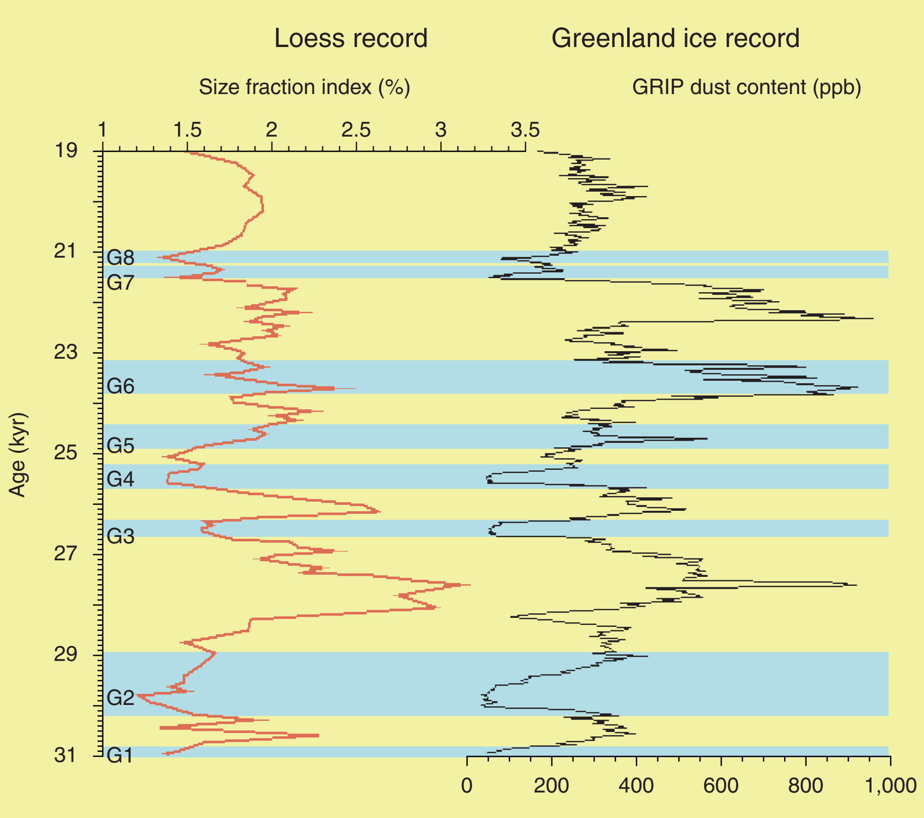


Figure 11 Comparison of the IGR grain size index at Nussloch and the GRIP dust record during the 35–15-kyr interval. After Rousseau DD, *et al.*, (2002). Abrupt millennial climatic changes from Nussloch (Germany) Upper Weichselian eolian records during the Last Glaciation. *Quaternary Science Reviews* **21**(14–15), 1577–1582.

$\delta^{18}O$ values in Greenland ice cores. Work within the EOLE project indicates that the warmest and longest interstadials are marked by well-developed paleosols (Bw horizon at the base of the thick sequence). In contrast, if the duration of the period of low dust concentration is short, then the interstadial will be marked in the stratigraphy by a gley paleosol, the signature of which will depend on the strength of the corresponding warming.

Variations in organic matter $\delta^{13}C$ support this interpretation, having been mainly linked to climatic fluctuations (availability of water and atmospheric CO_2 concentration) as recorded by the vegetation (Hatté *et al.*, 2001a, 1998). Warming during D/O events is also marked by larger terrestrial mollusk populations, as indicated by a greater abundance of counted individuals. Although the loess record and its correlation with Greenland is well documented at Nussloch, similar patterns, especially in the stratigraphy and also in the grain size variations, have been described all along the loess belt from northern France eastward to the Czech Republic and Ukraine, demonstrating again that European loess has faithfully recorded the climatic variations that occurred in the North Atlantic.

Summary

The loess of Europe is mostly an eolian sediment, generally presenting elements of both local and global origin. It is indicative of periglacial environmental conditions, which made the fine material available to wind transport, originating mainly from sandurs or dried-out braided rivers, moraines, or dried-out shelves. Considering their distribution, thickness, and complexity around the margins of the Quaternary ice sheets in the Northern Hemisphere, loess sequences can be considered as one of the best records of global environmental changes on the continents.

European loess sequences have been intensively studied for many decades, but increasingly higher stratigraphic resolution and availability of a growing range of climate proxy indicators have resulted in some notable advances in recent years. Climatic variability has been analyzed at high resolution based on different proxies. Sequences studied have revealed that the main loess deposition started at about 70 ka and ended around 16–15 ka. For example, the magnetic susceptibility record of the Achenheim loess sequence (France) has been

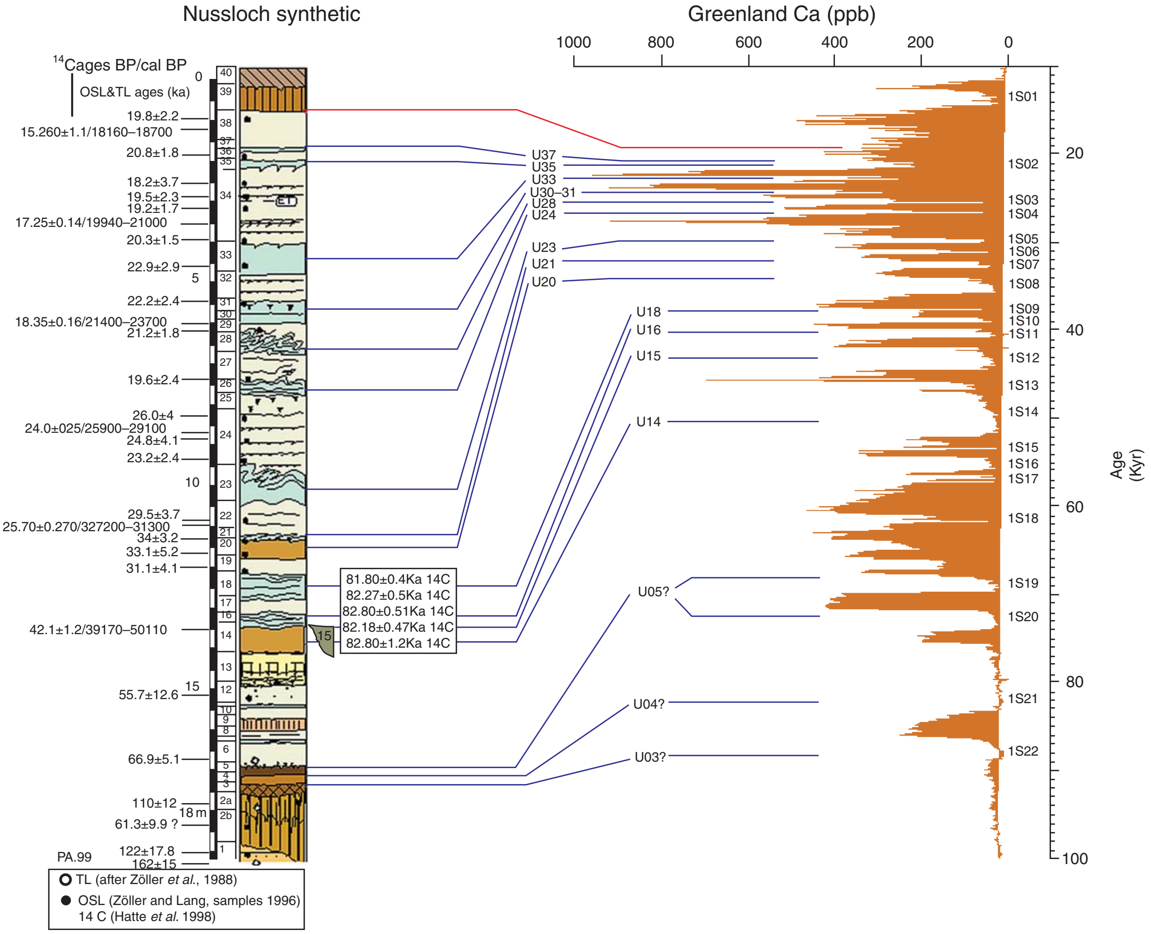


Figure 12 Pedostratigraphy of the Nussloch sequence compared with the Greenland dust record. After Antoine P *et al.*, (2001). High-resolution record of the Last Interglacial–glacial cycle in the loess palaeosol sequences of Nussloch (Rhine Valley-Germany). *Quaternary International* 76/77: 211–229; Rousseau DD, Antoine P, Hatté C, Moine O, (2003). Enregistrements des écénements rapides de type Dansgaard-Oeschger dans les séquences loessiques européennes *Lettre pigb-pmrc-France* **15**: 21–24.

correlated with the Upper Pleistocene (70–15 kyr) Greenland dust content. Other results have shown that abrupt changes, named markers, are also recorded in the soil complexes. Markers are generally finer grained than most loess, but mineral content does not differ significantly. These markers correspond to long-distance wind-transport episodes, recording clearly visible events. The results from the study of the Nussloch sequence (Rhine Valley) show that the loess sedimentation, *in sensu stricto*, is rhythmic, its fluctuations corresponding with rapid events of both marine and glacial type.

Analysis of particle size variation is a key method in loess research. Preliminary comparison of the grain size record from the Nussloch sequence, in the Rhine valley, and the dust content from the GRIP ice core in Greenland shows high-frequency peaks that correlate with dust content in ca. 1.5-kyr cycles, the main ones being associated to the North Atlantic Heinrich Events. This supports the hypothesis that European loess sequences contain a record of rapid climatic changes. Recently, work on δ^{13}C variations in organic matter from European loess sequences has shown that δ^{13}C parallels the GISP2 δ^{18}O variations, and is interpreted as recording the D/O events. Variation in this index was interpreted as recording the response of the local vegetation to climate changes. However, because there were no changes in the type of photosynthetic pathway, this index is also considered to be a proxy for local annual precipitation. In mid-latitudes, therefore, the dust intervals appear to correspond to periods when, although vegetation cover was reduced, it was adequate to provide sufficient organic matter from which to abstract a signal of biological activity (i.e., mollusks). The Greenland dust record also shows that isotope stages 2 and 4 were dustier than stage 3 and that important variations occurred in the dust content of the atmosphere during the same interval. Some of the oscillations were contemporaneous with the massive iceberg discharges named Heinrich Events.

See also: **Loess Deposits, Origins and Properties**. **Luminescence Dating**: Thermoluminescence; Optically-Stimulated Luminescence. **Paleoclimate Reconstruction**: Sub-Milankovitch (DO/Heinrich) Events. **Periglacial Landforms**: Cryoturbation Structures; Ice Wedges and Ice Wedge Casts. **Quaternary Stratigraphy**: Pedostratigraphy.

References

Antoine, P. (1991). Nouvelles données sur la stratigraphie du pléistocène supérieur de la France septentrionale, d'après les sondages effectués sur le tracé du TGV Nord. *Publications du CERP* **3**, 9–20.

Antoine, P. (1994). The Somme valley terrace system (northern France): A model of river response to Quaternary climatic variations since 800,000 BP. *Terra Nova* **6**, 453–464.

Antoine, P., *et al.* (2003a). The Pleistocene rivers of the English Channel region. *Journal of Quaternary Science* **18**, 227–243.

Antoine, P., Catt, J., Lautridou, J. P., and Sommé, J. (2003b). The loess and coversands of northern France and southern England. *Journal of Quaternary Sciences* **18**, 309–318.

Antoine, P., Lautridou, J. P., and Laurent, M. (2000). Long-term fluvial archives in NW France: Response of the Seine and Somme rivers to tectonic movements, climatic variations and sea level changes. *Geomorphology* **33**, 183–207.

Antoine, P., Munaut, A. V., and Sommé, J. (1994). Réponse des environnements aux climats du début glaciaire weichselien: Données de la France du Nord-Ouest. *Quaternaire* **5**, 151–156.

Antoine, P., Rousseau, D. D., Lautridou, J. P., and Hatté, C. (1999). Last interglacial–glacial climatic cycle in loess–paleosol successions of north-western France. *Boreas* **28**, 551–563.

Antoine, P., *et al.* (2001). High-resolution record of the Last Interglacial–glacial cycle in the loess palaeosol sequences of Nussloch (Rhine Valley-Germany). *Quaternary International* **76/77**, 211–229.

Antoine, P., *et al.* (2002). Evénements éoliens rapides dans les loess du Pléniglaciaire supérieur weichsélien: l'exemple de la séquence de Nussloch (Vallée du Rhin-Allemagne). *Quaternaire* **13**, 199–208.

Auffret, J. P., Horn, R., Larsonneur, C., Curry, D., and Smith, A. J. (1982). *La Manche orientale, carte des paléovallées et des bancs sableux. Bureau de Recherches Géologiques et Miniéres edit.*

Dansgaard, W., *et al.* (1993). Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature* **364**, 218–220.

Derbyshire, E., Billard, A., van Vliet-Lanoë, B., Lautridou, J.-P., and Cremaschi, M. (1988). Loess and palaeoenvironment: Some results of a European joint programme of research. *Journal of Quaternary Science* **3**, 147–169.

Derbyshire, E., and Mellors, T. W. (1988). Geological and geotechnical characteristics of some loess and loessic soils from China and Britain: A comparison. *Engineering Geology* **25**, 135–175.

Feng, X., and Epstein, S. (1995). Carbon isotopes of trees from arid environments and implications for reconstructing atmospheric CO_2 concentration. *Geochimica et Cosmochimica Acta* **59**, 2599–2608.

Frechen, M., Horváth, E., and Gábris, G. (1997). Geochronology of Middle and Upper Pleistocene loess sections in Hungary. *Quaternary Research* **48**, 291–312.

Frechen, M., Oches, E. A., and Kohfeld, K. E. (2003). Loess in Europe-mass accumulation rates during the Last Glacial Period. *Quaternary Science Reviews* **22**(1819), 1835–1857.

French, H. M. (1996). *The Periglacial Environment*. London: Longman.

Grabowska-Olszewska, B. (1988). Engineering – Geological problems of loess in Poland. *Engineering Geology* **25**, 177–199.

Grahmann, R. (1932). Der löss in Europa. *Mitteilungen der Gesellschaft für Erdkunde zu Leipzig* **51**, 5–24.

Haase, G., Haase, D., Ruske, R., Jäger, K. D., and Altermann, M. (2006). Loess in Europe – Spatial distribution in a scale 1 : 2,500 000. *Quaternary Science Reviews* (in press).

Haesaerts, P., Borziak, I., Chirica, V., Damblon, F., Koulakovska, L., and van der Plicht, J. (2003). The east Carpathian loess record: A reference for the Middle and Late Pleniglacial stratigraphy in central Europe. *Quaternaire* **14**, 163–188.

Haesaerts, P., Juvigné, E., Kuyl, O., Mucher, H., and Roebroeks, W. (1981). Compte rendu de l'excursion du 13 juin 1981, en Hesbaye et au Limbourg Neerlandais, consacrée à la chronostratigraphie des loess du Pleistocène supérieur. *Annales de la Société Géologique de Belgique* **104**, 223–240.

Haesaerts, P., *et al.* (2005). The loess–palaeosol succession of Kurtak (Yenisei Basin, Siberia): A reference record for the Karga stage (MIS 3). *Quaternaire* **16**(1), 3–24.

Hatté, C. (2000). Les Isotopes du Carbone (^{14}C et ^{13}C) Dans la Matière Organique des Loess de l'Europe du Nord-Ouest: Applications Paléoclimatiques, These de Doctorat, p. 175. Université Paris-Sud, Orsay.

Hatté, C., and Gauthier, C. (2006). *The loess war*.

Hatté, C., and Guiot, J. (2005). Paleoprecipitation reconstruction by inverse modelling using the isotopic signal of loess organic matter: Application to the Nussloch loess sequence (Rhine Valley, Germany). *Climate Dynamics* **25**, 315–327.

Hatté, C., *et al.* (2001a). δ ^{13}C of loess organic matter as a potential proxy for precipitation. *Quaternary Research* **55**(1), 33–38.

Hatté, C., Pessenda, L. C., Lang, A., and Paterne, M. (2001b). Development of accurate and reliable ^{14}C chronologies for loess deposits: Application to the loess sequence of Nussloch (Rhine Valley, Germany). *Radiocarbon* **43**(2B), 611–618.

Hatté, C., *et al.* (1998). δ^{13}C variations of loess organic matter as a record of the vegetation response to climatic changes during the Weichselian. *Geology* **26**(7), 583–586.

Hatté, C., *et al.* (1999). New chronology and organic matter δ ^{13}C paleoclimatic significance of Nussloch loess sequence (Rhine Valley, Germany). *Quaternary International* **62**, 85–91.

Horvath, E. (2001). Marker horizons in the loesses of the Carpathian Basin. *Quaternary International* **76/77**, 157–163.

Hradilova, J., and Stastny, M. (1994). Changes in the Clay Fraction Mineral Composition in a Loess Profile of the Last Interglacial and Early Glacial in Praha-Sedlec. *Acta Universitatis Carolinae Geologica* **38**, 229–238.

Juvigné, E. (1985). The use of heavy mineral suites for loess stratigraphy. *Geologie en Mijnbouw* **64**, 333–336.

Juvigné, E. H., and Wintle, A. G. (1988). A new chronostratigraphy of the late Weichselian loess units in Middle Europe based on thermoluminescence dating. *Eiszeitalter und Gegenwart* **38**, 94–105.

Kukla, G. (1977). *Pleistocene land-sea correlations. 1: Europe. Earth-Science Reviews* **13**, 307–374.

Kukla, G., An, Z. S., Melice, J. L., Gavin, J., and Xiao, J. L. (1990). Magnetic susceptibility record of Chinese Loess. *Transactions of the Royal Society Edinburgh: Earth Sciences* **81**, 263–288.

Kukla, G., and Cilek, V. (1996). Plio-Pleistocene megacycle: Record of climate and tectonics. *Palaeogeography, Palaeoclimatology, Palaeoecology* **120**, 171–194.

Kukla, G., and Koci, A. (1972). End of the Last Interglacial in the loess record. *Quaternary Research* **2**, 374–383.

Kukla, G., McManus, J. F., Rousseau, D. D., and Chuine, I. (1997). How long and how stable was the Last Interglacial? *Quaternary Science Reviews* **16**, 605–612.

Lang, A., *et al.* (2003). High-resolution chronologies for loess: Comparing AMS^{14}C and optical dating results. *Quaternary Science Reviews* **22**(10–13), 953–959.

Lautridou, J. P. (1974). La séquence loessique séquanienne du Würm á Saint-Pierre-les-Elbeuf. *Bulletin de l'Association Française pour l'Etude du Quaternaire* **40–41**, 242–243.

Lautridou J. P. (1985) *Le Cycle Périglaciaire Pléistocéne en Europe du Nord-Ouest et Plus Particuliérement en Normandie*. Thése Doctorat es Sciences Thesis, p. 908. Caen: Université Caen.

Lautridou, J. P., and Sommé, J. (1974). Les loess et les provinces climato-sédimentaries du Pléistocéne supérieur dans le Nord-Ouest de la France. Essai de corrélation entre le Nord et la Normandie. *Bulletin de l'Association Française pour ll'Etude du Quaternaire* **40–41**, 237–241.

Lautridou, J. P., *et al.* (1986). Corrélations entre sédiments quaternaires continentaux et marins (littoraux et profonds) dans le domaine France septentrionale-Manche. *Revue de Géologie Dynamique et Géographie Physique* **27**(2), 105–112.

Léger, M. (1990). Loess landforms. *Quaternary International* **7/8**, 53–61.

Lozek, V. (1990). Molluscs in loess, their paleoecological significance and role in geochronology – Principles and methods. *Quaternary International* **7/8**, 71–79.

Lyell, C. (1833). *The Principles in Geology*. John Murray, London.

Maruszczak, H., and Wilgat, M. (1995). Stratigraphical and paleogeographical interpretation of the results of heavy mineral analyses in loesses of Voidvodina. In *Problems of the Stratigraphy and Paleogeography of Loesses in Central Europe* (H. Maruszczak, Ed.), pp. 173–190. Anales Universitatis Mariae Curie_Sk_odowska.

Moine, O., Rousseau, D. D., Jolly, D., and Vianey-Liaud, M. (2002). Paleoclimatic reconstruction using Mutual Climatic Range on terrestrial mollusks. *Quaternary Research* **57**(1), 162–172.

O'Leary, M. H. (1981). Carbon isotope fractionation in plants. *Phytochemistry* **20**(4), 553–567.

O'Leary, M. H. (1988). Carbon isotopes in photosynthesis. *Bioscience* **38**(5), 328–336.

Oches, E. A., and McCoy, W. (1995). Amino acid geochronology applied to the correlation and dating of Central European loess deposits. *Quaternary Science Reviews* **14**, 767–782.

Pastre, J. F., Billard, A., Debard, E., Faure, M., and Guerin, C. (1996). A tephric horizon Mont-Dore provenance in the Plio-Pleistocene loessic sequence of Saint-Vallier (France). *Comptes Rendus de l'Académie des Sciences de Paris* **323**(7), 607–614.

Perederij, V. I. (2001). Clay mineral composition and palaeoclimatic interpretation of the Pleistocene deposits of Ukraine. *Quaternary International* **76/77**, 113–121.

Péwé, T. L. (1962). Ice wedges in permafrost. Lower Yukon River Area, near Galena, Alaska. *Biultyn Peryglacjalny* **11**, 65–76.

Pustovoytov, K., and Terhorst, B. (2004). An isotopic study of a Late Quaternary loess–paleosol sequence in SW Germany. *Revista Mexicana de Ciencias Geologicas* **21**(1), 88–93.

Pye, K. (1984). Loess. *Progress in Physical Geography* **8**, 176–217.

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

Rousseau, D. D. (1987a). Paleoclimatology of the Achenheim Series (Middle and Upper Pleistocene, Alsace, France) – A malacological analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology* **59**(4), 293–314.

Rousseau, D. D. (1987b). Paleoclimatology of the Achenheim series (Middle and Upper Pleistocene, Alsace, France). A malacological analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology* **59**, 293–314.

Rousseau, D. D. (1991). Climatic transfer function from Quaternary molluscs in European loess deposits. *Quaternary Research* **36**, 195–209.

Rousseau, D. D. (2001). Loess biostratigraphy: New advances and approaches in mollusk studies. *Earth-Science Reviews* **54**(1–3), 157–171.

Rousseau, D. D., Antoine, P., Hatté, C., and Moine, O. (2003). Enregistrements des écénements rapides de type Dansgaard-Oeschger dans les séquences loessiques européennes. *Lettre pigb-pmrc-France* **15**, 21–24.

Rousseau, D. D., Gerasimenko, N., Matviischina, Z., and Kukla, G. (2001). Late Pleistocene environments of the Central Ukraine. *Quaternary Research* **56**(3), 349–356.

Rousseau, D. D., Kukla, G., Zöller, L., and Hradilova, J. (1998a). Early Weichselian dust storm layer at Achenheim in Alsace, France. *Boreas* **27**, 200–207.

Rousseau, D. D., and Puisségur, J. J. (1990). A 350,000 years climatic record from the loess sequence of Achenheim, Alsace, France. *Boreas* **19**, 203–216.

Rousseau, D. D., Puisségur, J. J., and Lautridou, J. P. (1990). Biogeography of the Pleistocene Pleniglacial malacofaunas in Europe. Stratigraphic and climatic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology* **80**, 7–23.

Rousseau, D. D., Puisségur, J. J., and Lecolle, F. (1992). West-European molluscs assemblages of stage 11: Climatic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology* **92**, 15–29.

Rousseau, D. D., Zoller, L., and Valet, J. P. (1998b). Late Pleistocene climatic variations at Achenheim, France, based on a magnetic susceptibility and TL chronology of loess. *Quaternary Research* **49**(3), 255–263.

Rousseau, D. D., *et al.* (2002). Abrupt millennial climatic changes from Nussloch (Germany) Upper Weichselian eolian records during the Last Glaciation. *Quaternary Science Reviews* **21**(14–15), 1577–1582.

Rozycki, S. Z. (1991). Loess and Loess-ike Deposits, p. 187. Ossolineum-Polish Academy of Sciences., Wroclaw.

Shi, C., *et al.* (2003). Climate variations since the Last Interglacial recorded in Czech loess. *Geophysical Research Letters* **30**(11), 16, (doi:10.1029/2003GL017251).

Semmel, A. (1967). Neue Fundstellen von vilkanischem Material in hessischen Lössen. *Notizblatt des Hessischen Landesamtes fuer Bodenforschung zu Wiesbaden* **95**, 104–108.

Smalley, I. J. (1966). The properties of glacial loess and the formation of loess deposits. *Journal of Sedimentary Petrology* **36**, 669–676.

Smalley, I. J., Jefferson, I. F., Dijkstra, T. A., and Derbyshire, E. (2001). Some major events in the development of the scientific study of loess. *Earth-Science Reviews* **54**(1–3), 5–18.

Sommé, J., *et al.* (1986). Le cycle climatique du Pléistocéne Supérieur dans les loess d'Alsace é Achenheim. In *"Oscillations climatiques entre 125 000 ans et le maximum glaciaire. Corrélations entre les domaines marin et continental"* (M. T. Morzadec-Kerfourn, Ed.), 25–26, Bulletin de l'Association Française pour l'Etude du Quaternaire, 97–104.

Sommé, J., *et al.* (1994). The Watten boring – An Early Weichselian and Holocene climatic and palaeoecological record from the French North Dea coastal plain. *Boreas* **23**, 231–243.

Van Vliet-Lanoë B (1987) *Le Rôle de la Glace de Ségrégation Dans les Formations Superficielles de l'Europe de l'Ouest*. Doctorat es Sciences Thesis, p. 864. Université Paris I, Caen.

Van Vliet-Lanoë, B., and Coutard, J. P. (1984). Structures caused by repeated freezing and thawing in various loamy sediments: A comparison of active, fossil and experimental data. *Earth Surface Process Landform* **9**, 553–565.

Vandenberghe, J., Huijzer, B., Mücher, H., and Laan, W. (1998). Short climatic oscillations in a western European loess sequence (Kesselt, Belgium). *Journal of Quaternary Sciences* **13**, 471–485.

von Richtofen, F. (1882). On the mode of origin of the loess. *Geological Magazine* **9**, 293–305.

Wintle, A. G., Shackleton, N. J., and Lautridou, J. P. (1984). Thermoluminescence dating of periods of loess deposition and soil formation in Normandy. *Nature* **310**, 491–493.

Zöller, L., Stremme, H. E., and Wagner, G. A. (1988). Löss-Paläoboden-Sequenzen von Nieder-, Mittel- und Oberrhein. *Chemical Geology* **73**, 39–62.

Zöller, L., and Wagner, G. A. (1990). Thermoluminescence dating of loess – Recent developments. *Quaternary International* **7/8**, 119–128.

North America

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Introduction

The loess deposits of North America cover extensive areas of the midcontinent, northwestern US, and Alaska and neighboring parts of the Yukon Territory of northwestern Canada. The loess of North America is derived from both glaciogenic and nonglaciogenic sources, and source areas vary both spatially and temporally. The resultant deposits of wind-blown (eolian) silt and intercalated paleosols preserve important records of past climate and environmental conditions during the Quaternary. The loess deposits may act as both a sink and a source of dust, and recently it has been suggested that loess not only reflects changing climatic conditions, but may also potentially cause climate change through radiative forcing, and also through biogeochemical changes in atmospheric, terrestrial, and marine environments (Harrison *et al.*, 2001).

Distribution and Thickness of Loess Deposits

Loess is extensive over North America, particularly in the midcontinent region, Alaska, and the northwestern US (**Fig. 1**). The distribution of loess deposits in North America is governed primarily by the balance of supply of suitable sediment and the availability of conditions suitable for accumulation (Muhs *et al.*, 2003); These conditions for accumulation include vegetation and topography (Pye, 1996; Mason *et al.*, 1999); Source proximity, wind strength, and direction also influencing the pattern of loess distribution (Muhs and Bettis, 2000). In terms of their spatial extent, the principal areas of North America where loess deposits are preserved are: the midcontinent (incorporating the Great Plains and Central Lowland physiographic provinces) plus the Lower Mississippi Valley and the Wabash and Ohio River Valleys; the Pacific northwestern US (i.e., the Columbia Plateau physiographic province comprising two areas, the Columbia Plateau of eastern Washington and western Oregon, and the Snake River area of southern Idaho); plus Alaska and the neighboring Yukon Territory of northwestern Canada. The notable absence of areally extensive loess deposits in Canada is due to the fact that most of the area was covered by the Laurentide ice sheet during the last glacial period. Loess deposits are even lacking in those areas of Canada that were deglaciated first. The reason for this is not well understood, but it is likely that the large proglacial lakes, such as glacial Lake Agassiz, served as the sinks for most glaciogenic silt (Flint, 1971).

Maximum loess thicknesses in the North American midcontinent can exceed 60 m; in the Lower Mississippi Valley, bluffs composed of loess 20–30 m high are common (Markewich *et al.*, 1998), with maximum loess thicknesses occurring to the east of the valley (**Fig. 2**). In many locations in central North America, loess deposited during the last glacial period (Peoria Loess) accounts for more than 90% of the total loess thickness (Pye, 1987). The thickest known deposits of late glacial loess in the world occur in central Nebraska (48 m thickness at Bignell Hill), with considerable thicknesses of Peoria Loess also being found in Iowa (41 m at the Loveland Loess paratype) (Bettis *et al.*, 2003). In the Lower Mississippi valley, Peoria Loess is 10–20 m thick, but the thickness decreases with distance from the Mississippi River Valley with distance from the likely source areas. The present thicknesses of older loesses here, however, seem to be more closely linked to geomorphic position and degree of dissection than proximity of source (Busacca *et al.*, 2004).

The loess on the Columbia Plateau (**Fig. 3**) ranges from approximately 0.1 m to 75 m thickness, with the thickest deposits being found in an area straddling the eastern Washington/western Idaho border, called 'The Palouse' (Busacca and McDonald, 1994). Loess cover in the Columbia Plateau province beyond The Palouse is thinner and less continuous. Loess