

# European Loess Records<sup>☆</sup>

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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 ka 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 [Muhs](#) (this volume).

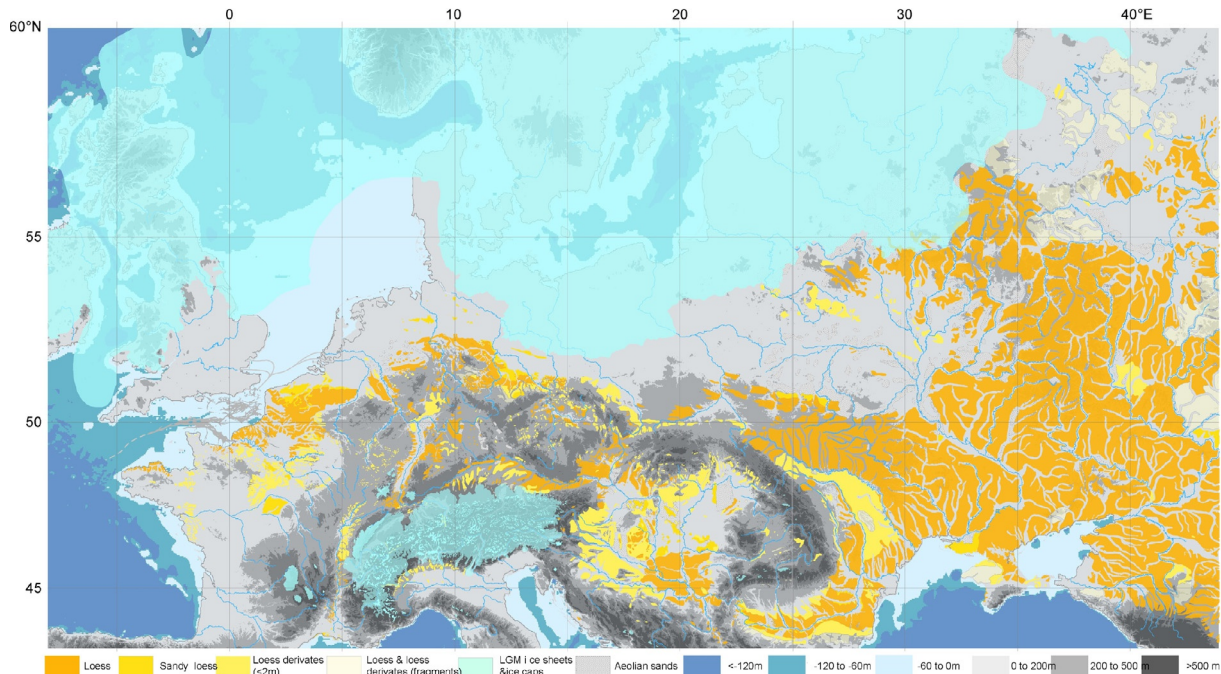
The discovery and first scientific description of European loess is attributed to [Karl Caesar von Leonhard \(1823/1824\)](#), noted pale yellow, unstratified sediment, containing snail shells and fossil root channels, in the Neckar River valley east of Heidelberg, Germany. He called it "loess," a local 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 (c. 40%–80%), the principal ancillary minerals 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

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**Fig. 1** Map of the main European loess deposits between 10° and 40° longitude and 60° and 45°N (after Antoine et al., 2013; Rousseau et al., 2014) with Last Glacial Maximum icesheets and ice caps extension. Reproduced from Rousseau et al. (2017b). (MIS3 & 2) millennial oscillations in Greenland dust and Eurasian aeolian records—A paleosol perspective. *Quaternary Science Reviews* **169**, 99–113.

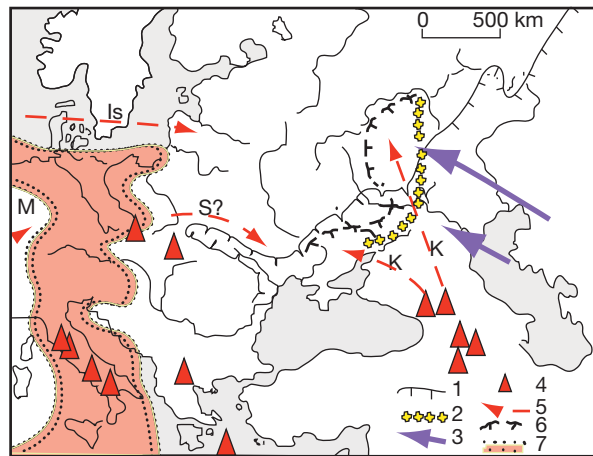
weight, have proved useful as indicators of provenance and degree of pedogenesis in both loess and paleosol units (Lautridou, 1985; Maruszczak and Wilgat, 1995). While the calcite-dolomite ratio is fairly consistent at about 3:1, carbonate content varies widely within Europe, for example, <11% in Poland, 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 inter-granular cements.

The finest fractions (clay grade: <2  $\mu\text{m}$ ) 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 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  $\mu\text{m}$  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  $\mu\text{m}$ ) in the south is approximately twice 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



**Fig. 2** Reach of dust of various origins transported by long-distance eolian transport in eastern and central Europe (after Rozycki, 1991). Key to symbols: 1—North-westerly 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.

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: Rozycki, 1991). Stratigraphically important volcanic tephra 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 tephra have been identified in European loess series as, for example, the volcanic ash fall out of the Bag tephra in Hungarian loess during marine isotope stages (MIS) 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) fall out during loess deposition in late MIS2 (Antoine et al., 2009a) contributing greater precision to the discussed age of this ash layer (Zöller et al., 1988; Juvigné and Wintle, 1988).

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 re-deposition, 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 re-deposited 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, noncalcareous 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 laminae 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 following the fast decay of the permafrost at the end of the Last Glacial.

In a preliminary study, Frechen et al. (2003) indicated mass accumulation rates (MARs) varying between 100 and 7000 g/m<sup>2</sup>/y, with particularly high values for Nussloch sequence in Germany (1213–6129 g/m<sup>2</sup>/y). These estimates are very different than those determined after reevaluating the chronology of the Nussloch key sequence (Rousseau et al., 2017a). In the reference sequence, MAR values vary between 376 and 1952 g/m<sup>2</sup>/y or between 395 and 1952 g/m<sup>2</sup>/y for Marine Isotope Stage (MIS) 3 and between 724 and 2586 g/m<sup>2</sup>/y or between 723 and 2515 g/m<sup>2</sup>/y for MIS2 when referring to the  $\delta^{18}\text{O}$  and dust-related Greenland ice-core chronologies respectively. These values are considered as the highest boundary values for these time intervals in European deposits.

### 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 (Sima et al., 2009).

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 (Sima et al., 2013).

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 sedimentation in Europe was controlled by sources of available dust. Thus, the main zones of deflation identified in Europe are the dried-out plains (paleo-estuaries) of the English Channel (Auffret et al., 1982; Antoine et al., 2003b) and the North Sea (Juvigné, 1985) 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 main alluvial plains occupied by braided channels during the Pleniglacial phases (times of maximum ice extent, roughly from 70 until 12 ka 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.

Geochemical results, obtained from European loess sequences collected along a 50°N transect, combined with dust emission simulations, reveal that the main dust contributors between 34 ka and 18 ka were in the same latitudinal band, with variable hot spots depending on climate conditions. These results demonstrate that most European dust traveled only over regional distances, only a few hundred kilometers or less, at low elevation, within the boundary layer, lower 3000 m of the atmosphere, from its source before deposition (Rousseau et al., 2014).

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

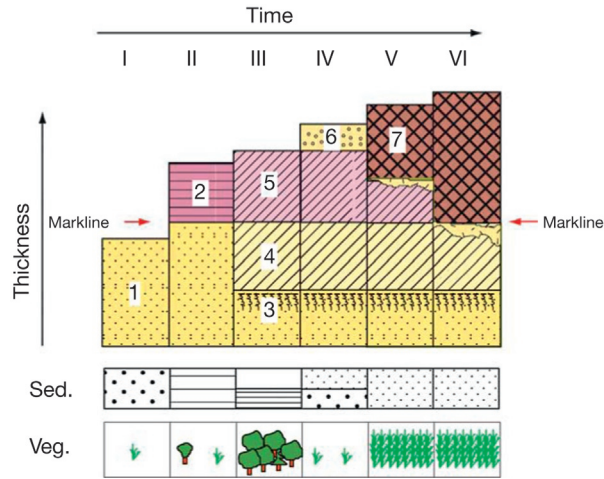
1. The platform loess, or “cover loess,” in western Europe, occurs as a mantle of relatively constant thickness. This loess is a homogeneous facies, characterized by considerable spatial continuity, that corresponds to the coldest and driest phases of the upper Pleniglacial of the Weichselian (~30–15 ka BP).
2. Slope deposits—more localized, and of variable thickness—these 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 ridges 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, 2009a). In the latter location, loess accumulation is mostly represented by upper Pleniglacial deposits (38–15 ka), 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; Liu et al., 1991). This cyclicity is expressed as an alternating series of loess and palaeosols that correspond to global glacial-interglacial climate cycles of 100 ka 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, Marker silt, 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 palaeoenvironmental conditions, and also provides a very useful tool for section-to-section correlation.

In the reference loess sequence of Dolní Vestonice (Czech Republic) such units were formed during intervals characterized by sparse vegetation—as identified by high  $\delta^{13}\text{C}$  values and low magnetic susceptibility—and they show finer grain size values, lower percentages in fine sand and higher ones in clay content than the overlying pleniglacial loess deposits. They are dated at about 111–109 ka and 93–2 ka, a last one at about 75–73 ka. Other dust horizons have been described corresponding to the loess material of Kukla’s cycles. These units are dated at about 106–105 ka, 88–86 ka, and 78.5–77 ka. These dates are determined by considering the OSL ages with their errors measured on the studied sequence and the comparison with Greenland ice-core and European speleothem chronologies (Rousseau et al., 2013).

All these eolian horizons correspond to short events of about 2 ka maximum in duration on the average; they are synchronous with advances of the polar front over the North Atlantic. They also correlate with abrupt changes observed in European vegetation. The comparison with the  $\delta^{18}\text{O}$  record from Northern Alps speleothems shows that, while the capping loess appear to be coeval with moisture supply from the North Atlantic, the marker silts do not show such a relationship. This decoupling between the two modes of dust deposition during MIS 5 differs from the pleniglacial situation, in which loess sedimentation in Europe tracks the Greenland dust record, while it is consistent with westerly transport. This occurrence of these dust events in the MIS 5 stratigraphy corresponds



**Fig. 3** Schematic development of soil complex in loess areas (after Kukla and Koci, 1972).

to a climatic mechanism that links polar-air outbreaks to blocking action associated with atmospheric circulation patterns that favor meridional flow (Rousseau et al., 2013). More recently, several dust storms have also transported red dust from the Sahara to Europe during the past 20–30 years (Goudie and Middleton, 2001).

Among the numerous European loess sequences, the Nussloch loess site, on the right bank of the Rhine valley, yields an important record of the last climate cycle (Antoine et al., 2001, 2009a). At this site, the sequence for the interval 60 ka to 18 kyr shows alternating paleosol and paleodust units preserved corresponding one to one with Greenland Interstadials (GI—paleosol) and Stadials (GS—paleodust) identified in the Greenland ice-cores (Dansgaard et al., 1993; Johnsen et al., 2001; Moine et al., 2008, 2017; Rousseau et al., 2002, 2007, 2017a, 2017b; Antoine et al., 2009a). The morphology of each paleosol observed at Nussloch is related to the duration of the corresponding GIs (Rousseau et al., 2007, 2017a, 2017b). GI 8, for example, the longest interstadial during the 38–15 ka period, corresponds, in the Nussloch stratigraphy to a well developed Arctic brown soil, while the much shorter GI 3 and 2, among others, correspond to tundra gley soils of variable thickness, or to weakly oxidized horizons marked, in part, by slightly increased organic contents (Rousseau et al., 2002, 2007, 2017a, 2017b; Antoine et al., 2009a). Uncertainties concerning the duration of soil formation periods pose important challenges in particular for the interglacial soils in which the upper profile is often eroded. Nevertheless, the Arctic brown and tundra gley paleosols do not show evidence of erosion on the outcrops. Furthermore, biological remains such as mollusk shells (Moine et al., 2008) and earthworm calcite granules (Prud'homme et al., 2016, 2017), encountered in the upper 10 cm of these paleosols, support the interpretation of lack of erosion. Duration of soil development is therefore proposed for the different paleosols observed, 180–880 years for the oxidized and tundra gleys and 1090–4200 years for the arctic brown soils. The succession of paleosol-loess unit couplets at Nussloch is not unique, but has been observed with local and regional variations in sequences ranging from Western Europe eastward to Ukraine (Antoine et al., 2009a, 2013; Rousseau et al., 2011, 2017a, 2017b).

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 paleosol 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, 2003a). 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, 1987), and indicates particularly cold conditions. In central Europe, the Krems and Red Hill sequences (Czech Republic) are famous for the long climatic history they preserve, stretching back to the Brunhes-Matuyama boundary at about 0.75 Ma (Kukla, 1977). Finally, Stari Slankamen sequence in Serbia recorded the last million years (Marković et al., 2011), establishing the base of a general Danube loess stratigraphy (Marković et al., 2015). The loess sequence at Starnzendorf (Austria) records the Gauss-Matuyama paleomagnetic boundary at about 2.5 Ma (Kukla et al., 1990).

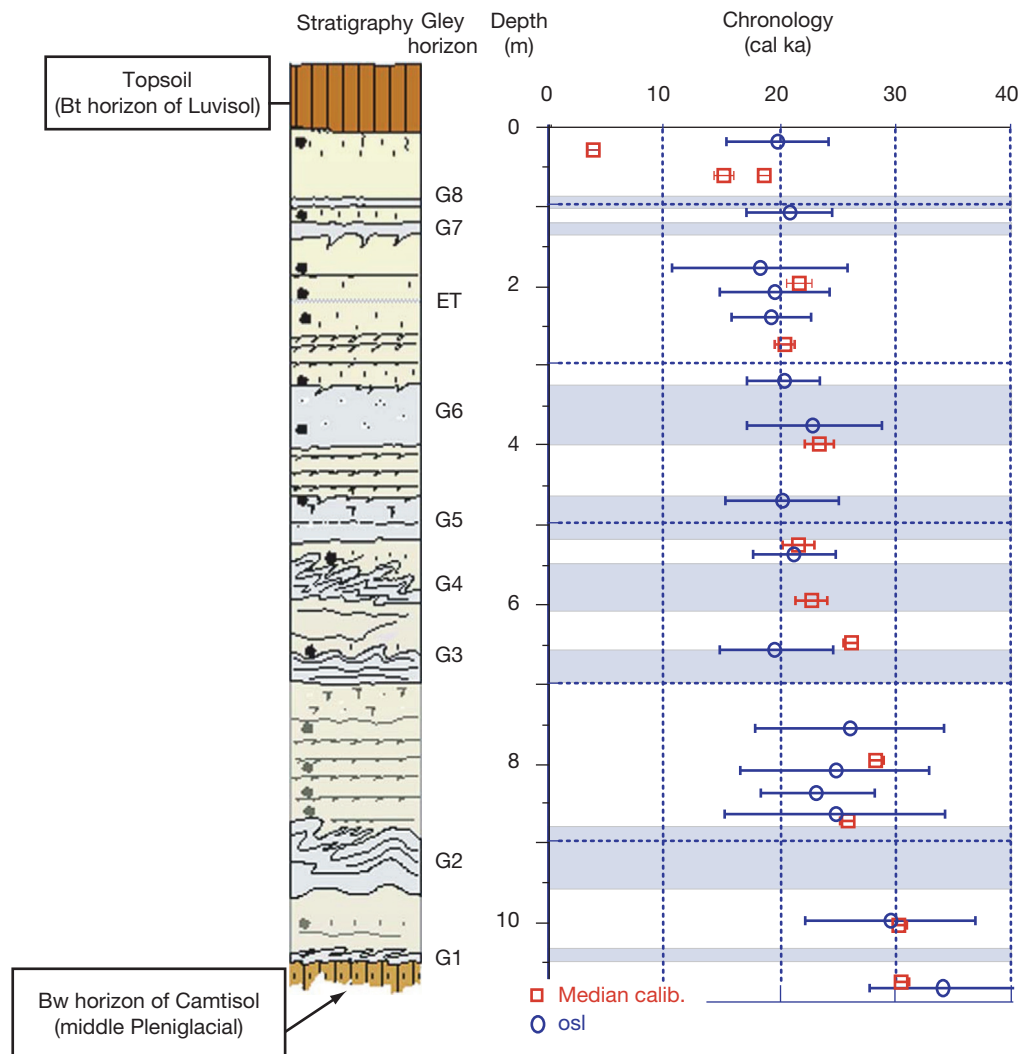
### Dating Loess in Europe: Geochronology

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; Zöllner 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.

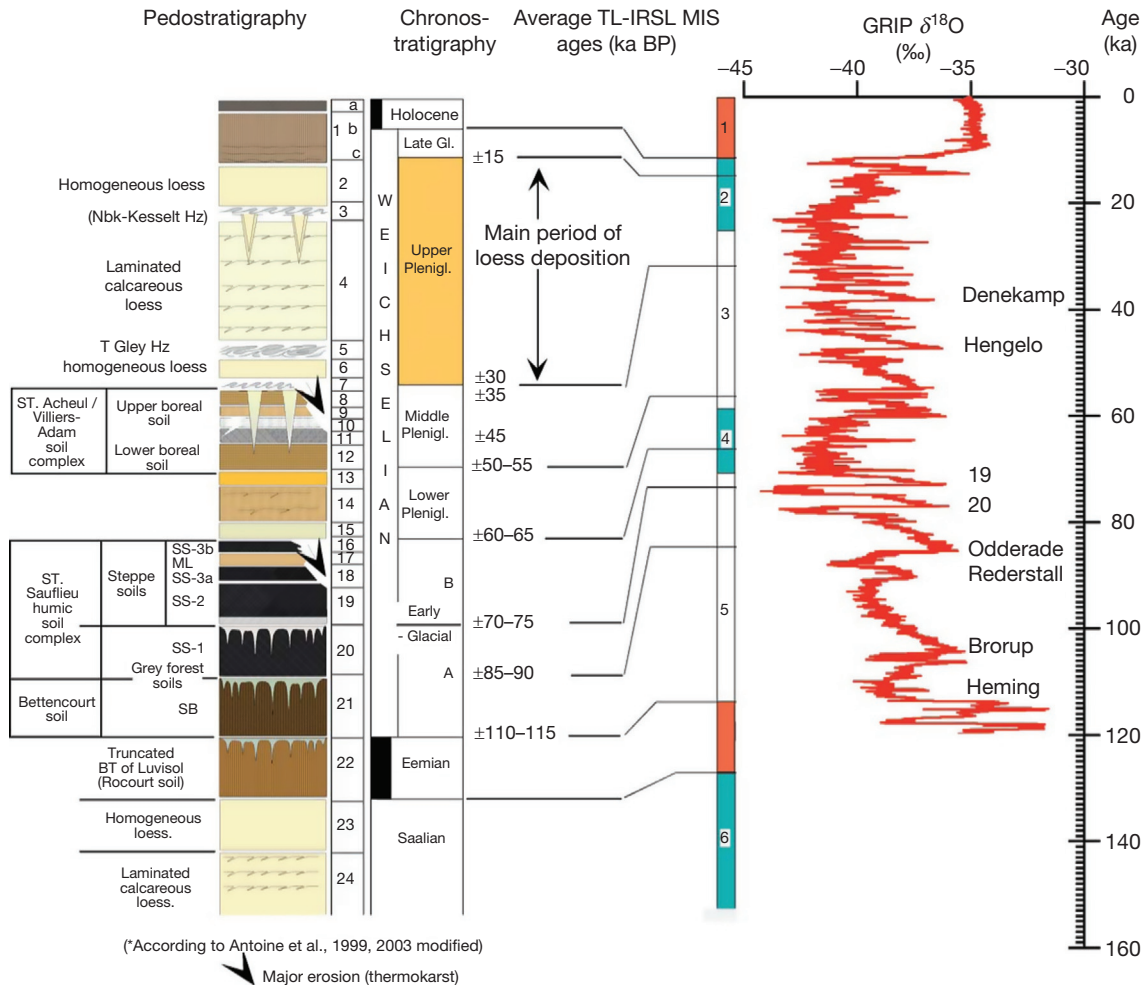
In Europe, the most common materials used for  $^{14}\text{C}$  dating are charcoal and wood. These materials are uncommon in loess, and are rarely distributed in an order that provides a continuous, high-resolution chronology, except in sequences close to human settlements (Haesaerts et al., 2010). A chronological framework was developed for the Nussloch loess sequence in Germany, based on AMS- $^{14}\text{C}$  dating of loess organic matter (Hatté et al., 2001a, 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., 2001b). 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,  $^{14}\text{C}$  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  $^{14}\text{C}$  chronology since vegetation is always present. The general difference between luminescence and  $^{14}\text{C}$  chronologies can be summarized by saying that the first characterizes a temporal framework in steps whereas the second smoothes and somewhat leads the first one (Fig. 4). Anyhow, all paleosols in Nussloch yield pure calcite granules secreted by earthworms living in these units, including the weakly oxidized horizons, during their development. Therefore, recent and new  $^{14}\text{C}$  dates from these concretions support the initial correlations showing that all the Greenland interstadials from 45 to 18 ka are preserved in the loess sequence (Moine et al., 2017).

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

Stratigraphic, paleopedologic, mollusk, earthworm and palynologic data, coupled with sedimentology, magnetic susceptibility and TL/IRSL ages provide a new picture of the last climatic cycle in northwestern Europe, and its connection with neighboring regions



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



**Fig. 5** Pedostratigraphy of the Upper Pleistocene in Western Europe (after Antoine et al., 1999).

(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, 2016). 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 continentalisation 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; Rasmussen et al., 2014). 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 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



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

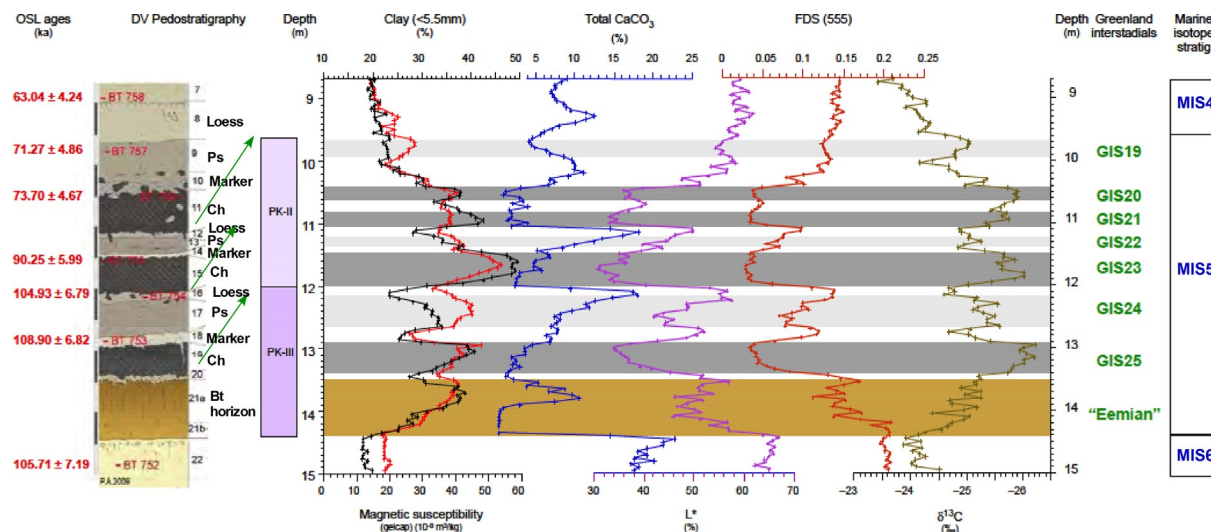
polygenetic horizon (Saint-Acheul). Elsewhere, in the sequences found in Villiers Adam, the loess is thicker (4 m) and contains four paleosols: a leached boreal soil, a humiferous arctic meadow soil (Van Vliet-Lanoë, 1987), a tundra gley, and an arctic brown soil.

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 ka 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 paleosol horizons (Antoine, 1991). The most common unit is the Nagelbeek/ “Kesselt” tongue horizon, dated to about 22 ka  $^{14}\text{C}$  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  $60 \pm 5$  ka and  $23 \pm 8$  ka BP, are separated by a period with much lower sedimentation rates of between  $\pm 55$  and 35 ka (Antoine et al., 1999, 2001, 2009a).

A similar sequence, with local variations due to the more continental conditions inferred from their geographical location, is available for central Europe (Kukla, 1977; Antoine et al., 2013; Rousseau et al., 2013) (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 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 (II), immediately followed by small pellet sands capped by another loess. This succession is repeated a second time with a thicker chernozem interrupted by Marker III 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 PK1. 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) or Stayky (Rousseau et al., 2011). In these sequences, 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 2500 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.





**Fig. 7** Continuous, quantitative characterization of the Dolni Vestonice soil complexes. On the left are OSL ages (mean  $\pm$  error) and the Dolni Vestonice pedostratigraphy defined in Antoine et al. (2013). Ch: Chernozem, Ps: Pelletsands. Reproduced from Rousseau et al. (2013). Major dust events in Europe during marine isotope stage 5 (130–74 ka): A climatic interpretation of the “markers”. *Climate of the Past* 9, 2213–2230.

## 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, molluscan paleo-zoogeography, earthworm paleoecology, 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 and Guiot, 2005; Hatté et al., 1998, 1999, 2001a; Pustovoytov and Terhorst, 2004). Others investigations are in progress in eastern Europe (Hatté et al., 2013). Organic geochemistry studies are based on the ‘fingerprint’ of environmental conditions provided by plant  $\delta^{13}\text{C}$ , and on its undisturbed conservation during burial and subsequent sedimentation. During photosynthesis, plants discriminate against  $^{13}\text{C}$  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  $\delta^{13}\text{C}$  of  $-13 \pm 2\%$ , whereas C3-plants, which prefer more temperate environments, present  $\delta^{13}\text{C}$  values around  $-26 \pm 4\%$  (O’Leary, 1988). Variability around the mean  $\delta^{13}\text{C}$  values in leaves of terrestrial vegetation (foliar  $\delta^{13}\text{C}$ ) results from environmental changes that influence stomatal conductance (e.g., Feng and Epstein, 1995). These results show that variation of the  $\delta^{13}\text{C}$  in C3 plants within the range  $-30$  to  $-22\%$  is primarily influenced by the  $\delta^{13}\text{C}$ , the concentration of atmospheric  $\text{CO}_2$  and by precipitation and, secondly, 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  $\delta^{13}\text{C}$  in atmospheric  $\text{CO}_2$ . 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 (Gauthier and Hatté, 2008), the carbon isotopic composition of loess organic matter is a powerful paleoclimatic indicator because it inherits the  $\delta^{13}\text{C}$  of growing plants that trap dust at the time of deposition. As environmental conditions and vegetation types (C3 vs. C4 photosynthetic pathways), control the  $\delta^{13}\text{C}$  levels in plants, the  $\delta^{13}\text{C}$  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,  $\delta^{13}\text{C}$  variations can be linked to first order changes in atmospheric  $\text{CO}_2$  ( $\delta^{13}\text{C}$  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 (70,000–12,000 years BP), whereas Pustovoytov and Terhorst (2004) exhibited some C4-carbon enriched layers ( $\delta^{13}\text{C}$  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,

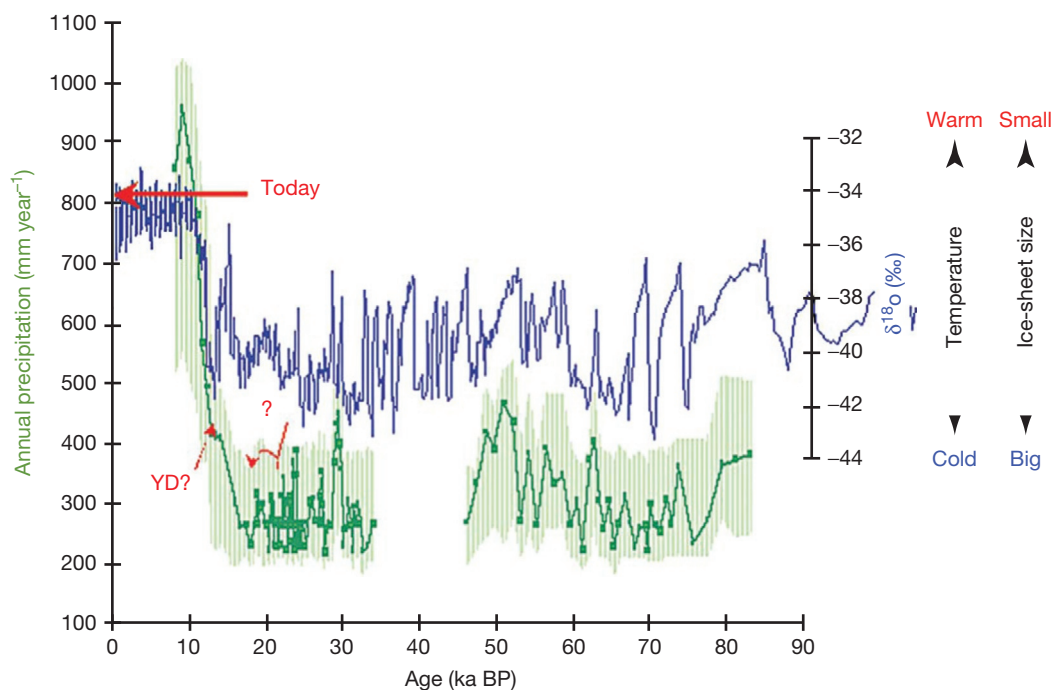
such as a mixture of C4 grasses and C3 trees. Nevertheless, and in contrast to all European loess sequences recorded along the last climatic cycle, with widespread C3 plant dominance, the organic  $\delta^{13}\text{C}$  record of Surduk and Dolni Vestonice are the only glacial records with several unquestionable records of C4 plants demonstrating different climatic conditions.

Considering the C3 photosynthetic pathway only, Hatté et al. (1998, 1999, 2013) interpreted the variations in the  $\delta^{13}\text{C}$  of loess organic matter in Nussloch (Germany, Rhine Valley) and Achenheim (France, Rhine Valley), but also from central Europe (Surduk in Serbia and Dolni Vestonice in Czech Republic) as a response to changes in paleoprecipitation patterns during the last glaciation. Using a linear relation between loess  $\delta^{13}\text{C}$  and atmospheric  $\text{CO}_2$  concentration and  $\delta^{13}\text{C}$ , on the one hand, and precipitation on the other, Hatté et al. (2001b) attempted a deconvolution of the loess  $\delta^{13}\text{C}$  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  $\delta^{13}\text{C}$  in Nussloch provided reconstructed paleoprecipitation values that varied between 240 and 400  $\text{mm year}^{-1}$  through the last glaciation (Hatté and Guiot, 2005). This clearly demonstrated atmospheric teleconnections with the Greenland Ice-sheet extension, by matching Dansgaard-Oeschger events with a precipitation increase of ca 100-200  $\text{mm year}^{-1}$  (Hatté and Guiot, 2005) (Fig. 8).

Bulk Last Glacial Maximum, about 24 ka, loess samples were geochemically analyzed from reference sequences located along a 50°N transect, chosen to represent the European geographic and petrographic variability. The samples have relatively uniform trace element patterns, with positive Zr-Hf anomalies due to an excess of zircon indicative of short-distance transport. The isotopic compositions of the analyzed loess samples form a separate cluster demonstrating that the sources of Nussloch sequence, Western Europe (including a sample from the English Channel), Eastern Germany, western Ukraine, and Serbian loess series are not identical as they have different initial ratios. The trace element data as well as the Sr and Pb isotopic data demonstrate that the sources of the loess deposits are proximal and different for each geographical region in agreement with numerical experiment performed with the Institut Pierre Simon Laplace (IPSL) Earth System model (ESM) (Rousseau et al., 2014).

### 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 versus 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 towards the surface, and so produce certain relief forms (tundra ostioles, soils with ice mounds).

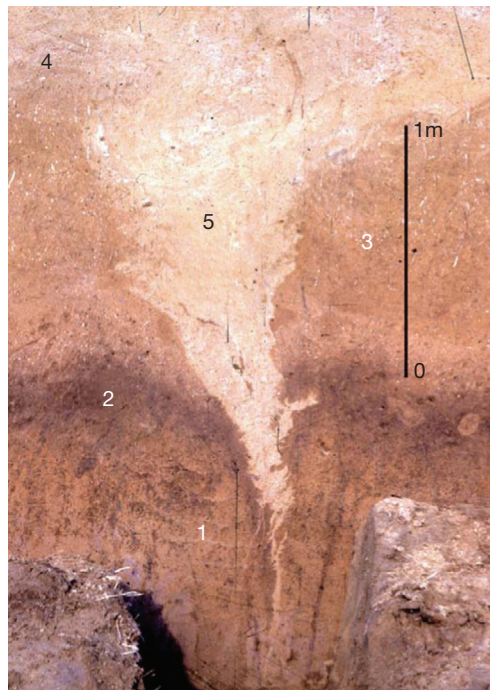


**Fig. 8** Reconstruction of annual precipitation in the Nussloch sequence (after Hatté and Guiot, 2005).

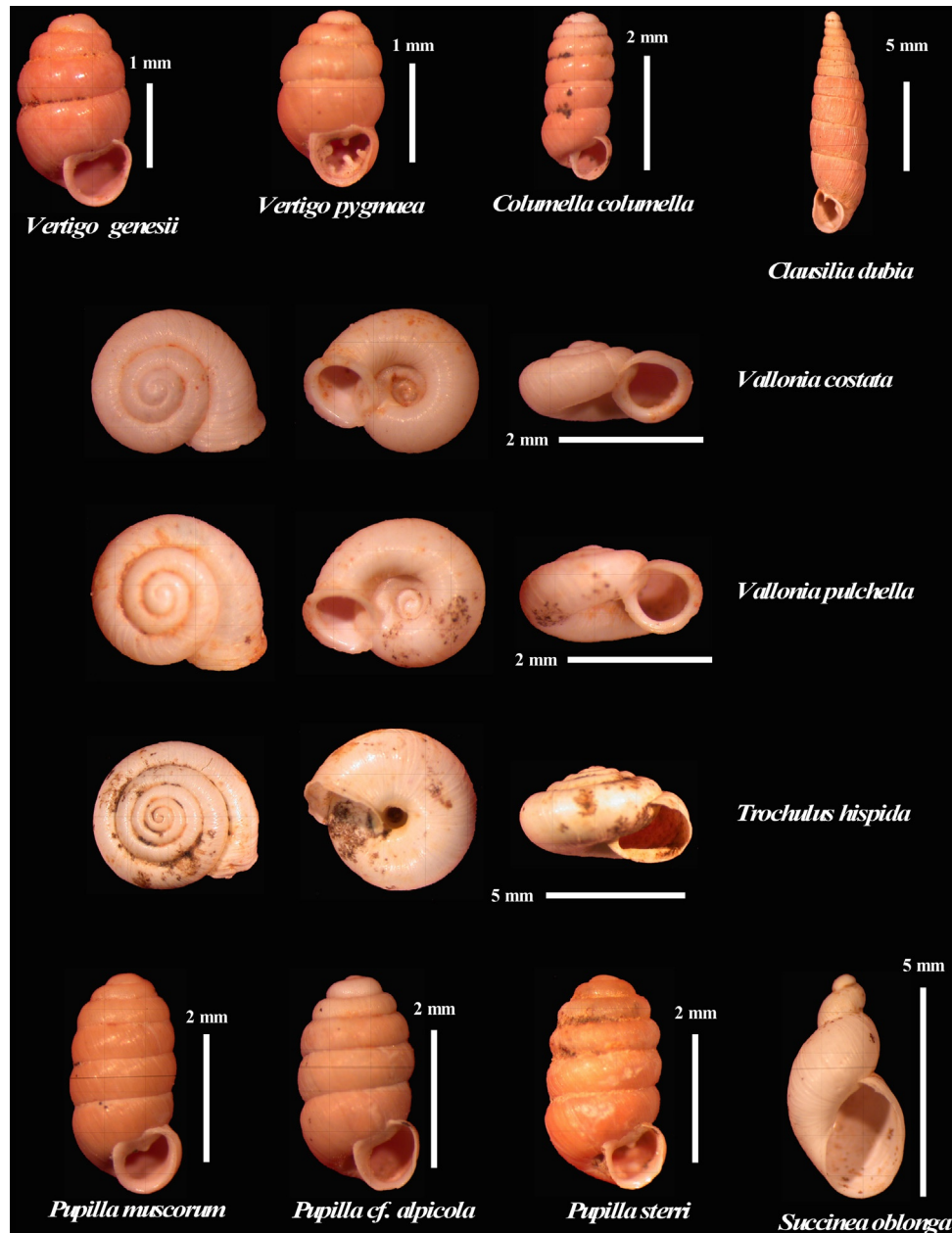
Ice wedge casts are produced from cracks caused by thermal contraction. They form progressively in a series of events, as follows: (1) cracking of the permafrost by thermal contraction in winter; and (2) infilling of cracks with meltwater produced by thawing of snow in spring, followed by re-freezing (French, 1996; Péwé, 1962). The development of these structures indicates the occurrence of permafrost, with a mean average atmospheric temperature lower than  $-8^{\circ}\text{C}$ , 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  $\pm 10\text{--}12\text{ m}$  wide. A recent compilation of the periglacial features like pingo or lithalsa scars, ice and sand wedges (Bertran et al., 2014; Andrieux et al., 2016) indicates that typical ice-wedge pseudomorphs does not extend south of  $47^{\circ}\text{N}$  in Western Europe.

### 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; Moine et al., 2008; Rousseau, 1987, 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 sequences has been interpreted as a response to the coldest and wettest conditions that prevailed in this area. In contrast, much less maritime (Atlantic) conditions characterized Central Europe during the last glacial period, where the assemblages were both more abundant and more diverse (Rousseau, 2001; Rousseau et al., 1990; Moine, 2014). Transfer functions of terrestrial mollusks, following the modern analogue principle, have been developed for European loess sequences, which show similar temperature reconstructions to those computed from pollen counts (Rousseau, 1991). 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 (Sümegei and Hertelendi, 1998). Terrestrial mollusks have also been studied for their  $^{14}\text{C}$  signature to date sequences, for their amino-acid signatures, which show significant differences from one climatic cycle to another (Oches and McCoy, 1995).



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



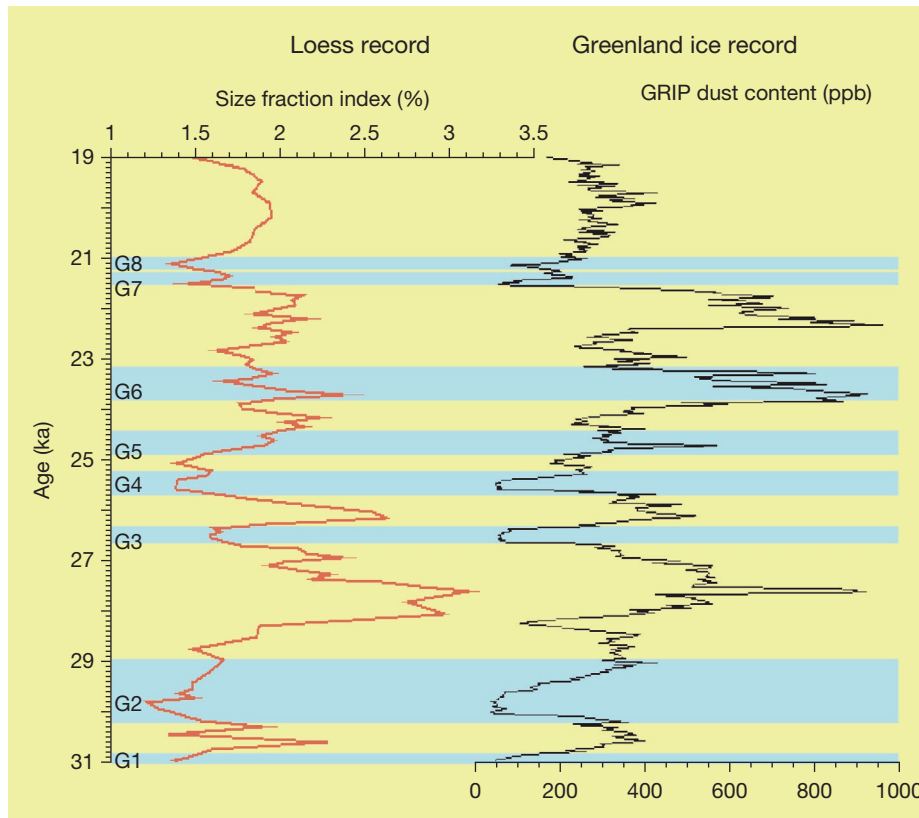
**Fig. 10** Main terrestrial mollusk species described from loess deposits. Photos by O. Moine.

### Earthworms Paleoecology, a New Paleoenvironmental Tool

Depending on the environmental conditions, earthworm present in loess unit or paleosols produced granules made of crystals of pure calcite. Sampling the Nussloch sequence, Prud'homme et al. (2015) showed that they are preserved in large quantities in paleosols compare to low numbers in loess units. Beside being used for  $^{14}\text{C}$  dating the individual paleosols (Moine et al., 2017), these granules can be analyzed for isotope geochemical study.  $\delta^{18}\text{O}$  study of the granules allows to reconstruct the soil and air temperature (Prud'homme et al., 2016) while the  $\delta^{13}\text{C}$  analysis allows the reconstruction of the precipitation (Prud'homme et al., 2017) of the warm season for both parameters during the paleosol developments.

### 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. A particular approach is



**Fig. 11** Comparison of the IGR grain size index at Nussloch and the GRIP dust record during the 35–15 kyr interval (after Rousseau et al., 2002).

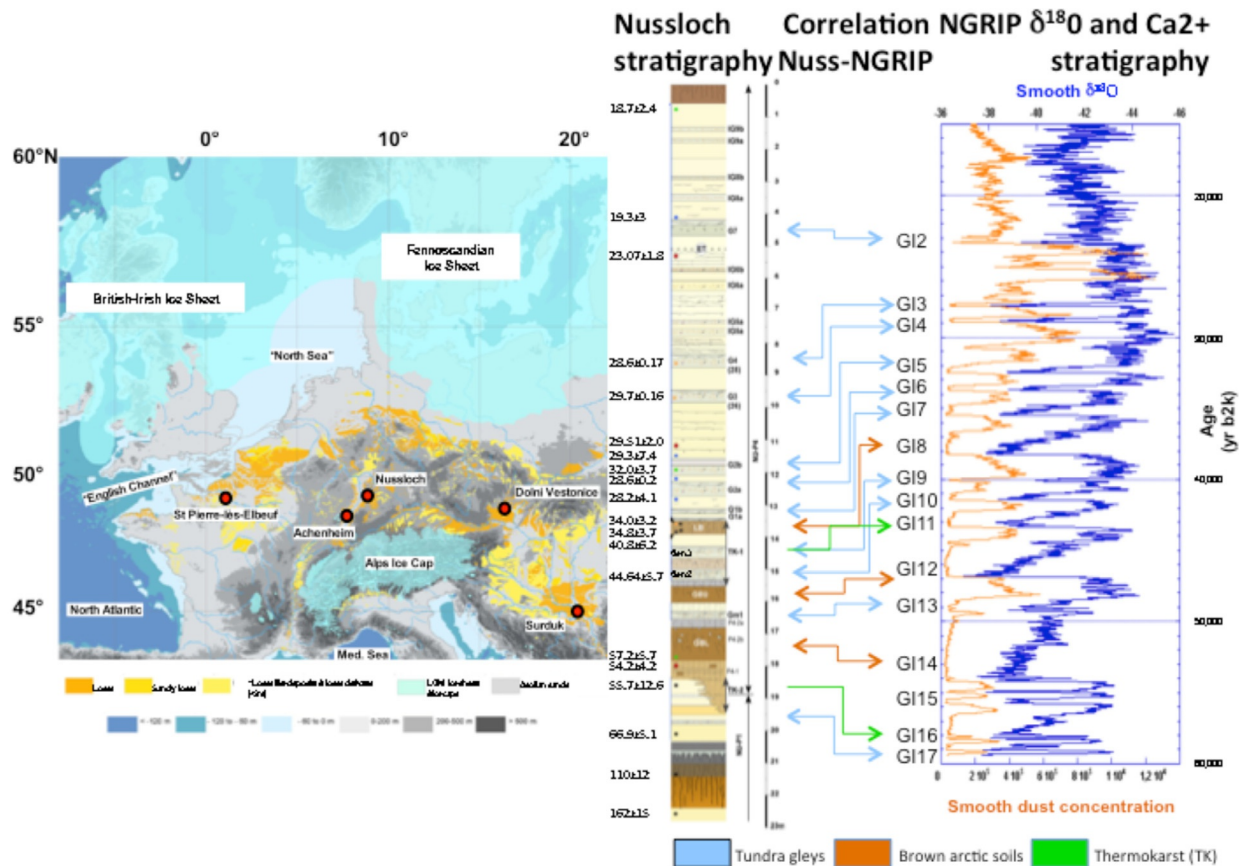
to define a grain size index, which corresponds to a ratio of two main particle size classes. Higher values indicate stronger winds. Two main indices have been developed. Studying the loess sequence at Kesselt in Belgium, Vandenberghe et al. (1998) defined the “U ratio” as the ratio between the two size classes 16–44 and 5.5–16  $\mu\text{m}$ . Similarly, in studying other European loess sequences, (Antoine et al., 2002; Antoine et al., 2009a, 2009b, 2013) developed the IGR index ratio defined as the ratio between coarse loam (20–50  $\mu\text{m}$ ) and fine loam and clay (<20  $\mu\text{m}$ ), which is similar to the “U ratio” (Fig. 11). 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 (Rousseau et al., 2011).

### 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.

Considerable interest is brought on the abrupt climate changes that punctuated the last glacial period (~110.6–14.62 ka). Originating in the North-Atlantic area, they have been recorded in ice, marine and terrestrial records all over the world, and especially in the Northern Hemisphere, with various environmental implications. The ice-core records, of increasingly high resolution, allow specifying more precisely the timing of these abrupt changes, which have occurred within intervals equivalent to present human generations. The continental records have been mainly interpreted so far in terms of temperature, precipitation or vegetation changes between the relatively warm (“Greenland Interstadial”—GI) and the cold (“Greenland Stadial”—GS) North-Atlantic climate phases.

The comparison of Greenland ice-core records and northwestern European eolian deposits establishes a link between GI and the soil development in European mid-latitudes, as recorded in loess sequences. For the different types of observed paleosols, the precise correlation with the Greenland records is applied to propose estimates of the maximum time lapses needed to achieve the different degrees of maturation and development (Fig. 12). To identify these time lapses more precisely, two independent ice-core records are compared:  $\delta^{18}\text{O}$  and dust concentration, indicating variations of temperature and atmospheric dustiness respectively in the Greenland area (Rousseau et al., 2017b). This method slightly differs from the definition of a GI event duration applied



**Fig. 12** Stratigraphic correlations between Nussloch paleosols and NGRIP interstadials (GIs) (modified from Rousseau, D. D. et al. (2017b). Eurasian contribution to the last glacial dust cycle: how are loess sequences built? *Climate of the Past* **13**, 1181–1197. doi: 10.5194/cp-2017-5167. Map as in Fig. 1.  $\delta^{18}\text{O}$  (‰, in blue) and the dust concentration ( $\text{part}/\mu\text{L}$ , in brown) records in the NGRIP ice core over the interval between 60 and 15 ka b2k. Nussloch stratigraphic column from Antoine, P. et al. (2016). Upper Pleistocene loess-paleosol records from Northern France in the European context: Environmental background and dating of the Middle Palaeolithic. *Quaternary International* **411**, 4–24. doi: 10.1016/j.quaint.2015.11.036 modified. Reproduced from Rousseau, D. D. et al. (2017a). (MIS3 & 2) Millennial oscillations in Greenland dust and Eurasian aeolian records—A paleosol perspective. *Quaternary Science Reviews* **169**, 99–113.

in other studies where the sharp end of the  $\delta^{18}\text{O}$  decrease gives the end of a GI. The same methodology is applied to both records (i.e., the GI last from the beginning of the abrupt  $\delta^{18}\text{O}$  increase or dust concentration decrease until when  $\delta^{18}\text{O}$  or dust reach again their initial value) determined both visually and algorithmically, and compare them to GI published estimates.

Numerical simulations using the IPSL ESM have improved our understanding of some of the mechanisms connecting the millennial-scale variations of the North-Atlantic climate to the loess sedimentation in Europe around the 50°N parallel. The modeling results point to vegetation changes in response to the millennial climate variability as a key factor in modulating dust emission (and consequently, also deposition). They also show the strong seasonality of the dust cycle, mainly active in springtime, when the snow cover melts, top-soils begin to thaw, surface winds are still strong (even though weaker than in winter), and the surface is exposed to wind erosion due to weak vegetation development. The colder the climate, the later the emission season starts, and the later it ends (about 1 month delay for a given region between the warmest and the coldest simulated climate state, GI vs. GS) (Sima et al., 2009, 2013).

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; 2017 a,b).

Focusing on the eolian/dust intervals, the analysis of  $\delta^{18}\text{O}$  and dust in the Greenland ice cores, and a critical study of their source variations, reconciles these records with those observed on the Eurasian continent. This allows demonstrating the link between European and Chinese loess sequences, dust records in Greenland, and variations of the North Atlantic sea ice extent (Rousseau et al., 2017a). The sources of the emitted and transported dust material are variable and relate to different environments corresponding to present desert areas in Asia, but also hidden regions related to lower sea level stands, dry rivers, or zones close to the frontal moraines of the main Northern Hemisphere ice sheets in Europe.

Although the loess record and its correlation with Greenland is well documented at Nussloch, similar patterns, especially in the stratigraphy but 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 has 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 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, NGRIP ice cores in Greenland shows high frequency peaks that correlate with dust content in ca. 1500 year cycles, the main ones being associated to the North Atlantic Heinrich events. The exact dating of the observed paleosols allow correlating them, one to one, with Greenland interstadials. This supports the hypothesis that European loess sequences contain a record of rapid climatic changes and allows determining the duration of soil maturation for the different categories of paleosols noticed (Arctic brown soil, tundra gley, embryonic soil). Analysis of  $\delta^{13}\text{C}$  variations in organic matter from European loess sequences has shown that  $\delta^{13}\text{C}$  parallels the GISP2  $\delta^{18}\text{O}$  variations, and is interpreted as recording the Dansgaard-Oeschger 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, earthworms). The Greenland dust record also shows that Marine Isotope Stages (MIS) 4 and 2 were dustier than MIS 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.

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