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Loess in Europe—mass accumulation rates during the Last Glacial Period

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Abstract

Upper Pleistocene loess/palaeosol sequences provide excellent high-resolution terrestrial archives of climate forcing. Due to improvements in numerical age determinations, especially in luminescence dating methods, a more reliable time-based reconstruction of the past climate and environmental change has become available for the loess record in Europe. Chronological information was collected from 43 sites along a northwest to southeast transect in Europe. Thirty-three of these sites had sufficient age information to allow estimation of mass accumulation rates, and it was possible to isolate the mass accumulation rates of primary loess during the Last Glacial Period (~28–13 ka BP) at 21 of these locations. These sites fall along a coarse climatic gradient from the relatively coastal climate of Belgium and France to the drier, more continental climate of Central Europe. Interpreting mass accumulation rates of loess in terms of this climatic gradient is not straightforward as these deposits are dominated by sources in floodplains and large river systems. Thus accumulation rates are influenced strongly by regional wind and precipitation patterns, but mostly by the availability of glacially derived material from the Alps and the periglacial terrains that characterized European fluvial systems during and immediately following glaciation.

1. Introduction

The loess record of Europe provides a potentially important archive of regional climate change. However, interpreting the relationships between European climate and other parts of the Northern Hemisphere requires adequate chronological control for determining the relative timing of various climatic events. It was Kukla (1970) who first attempted to correlate the terrestrial archives of the loess deposits from Moravia with the marine climate records for which the oxygen isotope time scale had been established (Emiliani, 1955). Fink and Kukla (1972) extended the record for the whole Quaternary. The difficulties involved in using such a correlative approach in the absence of reliable independent age control arise from the fact that terrestrial records are frequently incomplete as a result of erosional events (e.g. Boenigk and Frechen, 1998).

The Last Glacial loess record has become of major interest because chronological methods such as luminescence dating make possible the direct determination of deposition ages of aeolian sediments and therefore circumvent some of the problems associated with simple stratigraphic correlation. High-resolution luminescence dating studies using a multiple sample approach have been successfully applied to Upper Pleistocene loess and loess derivatives (Frechen, 1992, 1999a; Frechen et al., 1995, 1997, 2001a; Frechen and Dodonov, 1998; Lang et al., 2003). Multidisciplinary research on thick accumulations of loess with intercalated palaeosols has become attractive because these sediments provide a detailed terrestrial archive of climate and environmental change throughout the Northern Hemisphere for the Quaternary Period (Kukla, 1975, 1977; Liu, 1985; Pécsi, 1990; Shackleton et al., 1995; Frechen, 1998, 1999b; Antoine et al., 1999; Boenigk and Frechen, 2001).

With the help of chronological information, primarily based on luminescence, the direct dating of depositional events makes it possible to compute mass accumulation rates for loess. The reason for calculating mass accumulation rates as fluxes (in g/m^2/yr) as opposed to

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simple sedimentation rates (mm/yr), is that such units are directly comparable to the aeolian records in deep-sea sediments or ice cores used to assess the role of dust in climate change (e.g. Mahowald et al., 1999; Kohfeld and Harrison, 2000, 2001; Harrison et al., 2001); thus, the addition of mass accumulation rates from an increasing number of terrestrial sites contributes to a more global picture of aeolian flux during the Last Glacial Period.

In this paper, information from 43 sites that form a northwest–southeast transect across Europe has been compiled from the literature in order to obtain accurate chronologies for the time period of oxygen isotope stage 2 (OIS 2) between 28 and 13 ka BP, from which accumulation rates may be determined. The aim of this paper is to present an overview of loess chronology in Europe and to provide, for the first time, an estimate of mass accumulation rates (MARs) for OIS 2.

1.1. European loess chronostratigraphy of the past 130,000 years

During Quaternary glaciations, a great part of Europe experienced increased dust accumulation and loess formation (Grahmann, 1932), ranging from NW France and Belgium with its mainly maritime-influenced climate to Central Europe, Ukraine, and the Russian Plain with its more continental climate (Fig. 1). The origin of loess in Europe is still controversial (Pye and Sherwin, 1999). It has been proposed that the silt-sized particles in loess are derived from multiple-recycled and well-mixed ancient sediments from sources bordering the English Channel and the Atlantic coast (Smalley and Leach, 1978). Gallet et al. (1998) pointed out that European loess must have undergone previous sedimentary differentiation and was subjected to a moderate degree of chemical weathering. The oldest loess deposits are older than the last magnetic polarity change at about 790 ka BP (Brunhes/Matuyama boundary) and were most likely deposited about one million years before present (BP) (Fink and Kukla, 1972). About one million years ago, the orbital obliquity at 41 ka cycles, which had dominated the earlier part of the Pleistocene was superceded progressively by a 100 ka rhythm of orbital eccentricity, crucially accompanied by increased-amplitude climatic oscillations. As a consequence, the increased glaciation of the Alps and Scandinavia has resulted in the availability of large amounts of fine-grained silt to produce loess.

In Europe, loess/palaeosol sequences have been intensively studied during the past century. These deposits display a wide variety of climate proxies, and which therefore supply some clues about major climate and environment changes on land during the past 130,000 years. Loess is a predominantly silt-sized clastic sediment, which is formed by the accumulation and diagenesis of wind-blown dust. According to Pye (1995) four fundamental requirements are necessary for its formation: a dust source, adequate wind energy to transport the dust, a suitable accumulation area and a sufficient amount of time. During the Quaternary, loess and loess-like sediments were formed in periglacial environments on mid-continental shield areas such as in Central Europe and Siberia, on the margins of high mountain ranges such as in the piedmont area of Central Asia and on semi-arid margins of some lowland deserts such as in China.

The term "Löß" (loess) was first reported by von Leonhard (1823/24) who described the yellowish brown silty deposits along the Rhine valley near Heidelberg, Germany. Lyell (1834) brought the term into widespread usage by visiting the Rhine and Mississippi

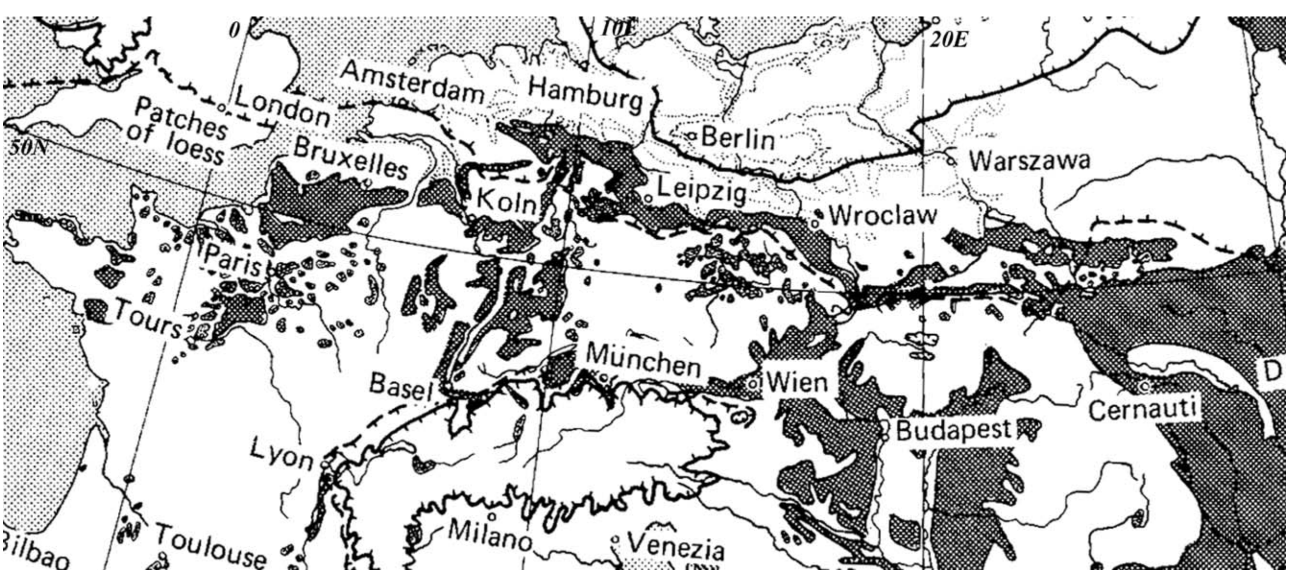

Fig. 1. Distribution of loess in Europe (part of the map by Grahmann (1932), as re-drawn in Flint (1971)).

valleys, observing the similarity of loess and loess derivatives in both areas along the loess bluffs. The aeolian origin of loess has been accepted since the work of Virlet d'Aoust (1857) and Richthofen's (1878) observation and interpretation of loess from China. Obruchev (1911, 1948) stressed the importance of wind action in the accumulation of loess. Recent summaries on the formation of loess and overviews on loess research were presented by Derbyshire (1995a, b); Pécsi and Richter (1996); Pye (1987, 1995) and Smalley (1995).

From a European point of view, the "classic approach" in loess research involves the application of methods such as sedimentology, pedology, and faunal and floral remains in order to classify and obtain scientifically based estimates of past environmental change. A major problem with such an approach is insufficient independent age control. Therefore, it is often not possible to correlate these sequences or horizons from site to site or from region to region. A reliable chronological framework is essential for continuing improvements in the reconstruction of climate and environmental changes.

Loess deposits include a variety of cold and warm climate indicators and provide a long-term record of climate change in the Quaternary. Snail faunas, such as "*Pupilla*", "*Columella*" and "*Striata*" are designated to represent cold and dry climate ("loess steppe"), cold and humid subarctic climate and cold winter/warm summer ("warm loess steppe"), respectively (Lozek, 1964, 1969). Typical mollusks in interglacial soils are those of the "Banatica fauna" (Lozek, 1969) indicating a warm-climatic environment. Skeletal remains of large mammals such as mammoth, woolly rhinoceros, moschus or reindeer are cold climate indicators as well. Remains of mammals, such as *Elephas antiquus*, *Cervus dama* and *Sus scrofa*, are interglacial species. Pollen is not usually well preserved in loess (Urban, 1983; Bittmann, 1991), although pollen preservation is often better in loess-derived palaeosols, which may provide information that distinguishes discrete climatic cycles within an interglacial period. Periglacial features are common in loess, including ice wedge casts, solifluction, gelifluction, drop structures and periglacial slope wash deposits, as summarized by French (1996).

2. Northwestern Europe

In northwestern France and Belgium, a truncated Bt horizon within a brown leached soil of the Eemian interglacial period indicates the presence of deciduous forest; this soil correlates with oxygen isotope sub-stage 5e of the deep sea record, as summarized by Haesaerts et al. (1999), Antoine et al. (2002) and van den Haute et al. (2003). The Rocourt sequence (site 4, Fig. 2) in Belgium is the reference section of the Eemian interglacial soil called the "Rocourt Soil "or "Sol de Rocourt" in northwestern Europe (Gullentops, 1954).

The loess-palaeosol record of the Lower Weichselian, which correlates with OI sub-stages 5d–a of the marine record, is well exposed at the section at Saint Sauflieu (site 7) near Amiens in France (Engelmann and Frechen, 1998; Antoine et al., 1999, 2002). There, a grey forest soil (Saint-Sauflieu-1), most likely formed under a boreal forest dominated by birch and pine. This soil is correlated with the two Early Glacial Brörup and Odderade interstadials, which are in turn correlated with OI sub-stages 5c and 5a (Antoine et al., 1999). The transition between OIS 5 and OIS 4 around 73 ka BP

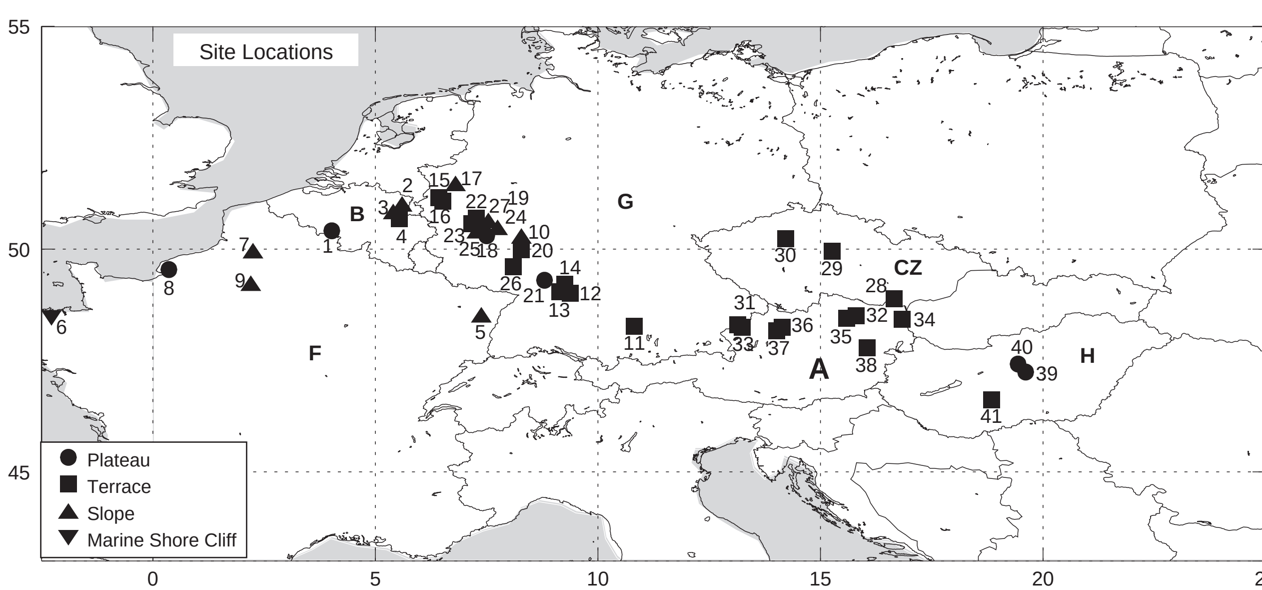

Fig. 2. Locations and geomorphological environments, or site types, of the OIS 2 loess considered in this paper.

was characterized in the loess record by a period of climatic instability, as recorded by the formation of steppe soils (known as Saint-Sauflieu-2 and -3) and the contemporaneous occurrence of aeolian dust accumulation (Antoine et al., 2002). During the early part of the Middle Weichselian (OIS 3) between 65 and 55 ka BP, loess was deposited in NW France along the River Seine and its tributaries. Several soil forming periods followed; these are, from bottom upwards an Arctic brown soil, a gelic cambisol, an Arctic brown soil and a tundra gley, as exposed at the section at Villiers-Adam (site 9) about 35 km to the north of Paris (Locht et al., 2003). These palaeosols probably formed between 55 and 35 ka BP. The latter tundra gley is covered by reworked layered loess and a second brown arctic soil, which formed at the end of the Middle Weichselian. The top of the sequence consists of calcareous loess with intercalated gelic gleysols with ages of between 25 and 20 ka BP. At Saint Sauflieu, Lateglacial loess was deposited between 18 and 13 ka BP. This section is situated at the base of a slope so that most of the sediment consists of slope wash.

In Brittany, the Bay of Saint Brieuc was a source of large amounts of calcareous silt-rich sediments. The section at Sables d'Or les Pins, (site 6) situated at a shore cliff, has a detailed Upper Weichselian loess record. The sequence consists of Pleniglacial and Lateglacial loess ranging from 26.4 to 19.7 ka BP and from 17.8 to 15.9 ka BP, respectively (Monnier et al., 1997). The Holocene pedocomplex and Late Holocene dune sands overlie the loess. Lateglacial loess is exposed at the section at Saint Romain, (site 8) about 20 km west of Le Havre in Normandy (Lautridou, 1992). Here, TL dating gave ages between 12.6 and 16.4 ka BP (Wintle et al., 1984). The Pleniglacial loess, from the section at Villiers-Adam (site 9) in the Oise River valley, yielded a luminescence age estimate of 23.5 ka BP (Locht et al., 2003). Antoine (1990) compiled a summary of additional exposures containing Pleniglacial and Lateglacial loess along the River Somme, although numerical dating results are not yet available for these sites.

In Belgium, the section at Harmignies (site 1), about 5 km southeast of Mons, is one of the most important sites for the Upper Pleistocene loess record in NW Europe (Haesaerts and van Vliet, 1973; 1981; Frechen et al., 2001). Its location, in the loess belt south of the Rhine-Maas delta and west of the Eifel area, makes it a key site for long-distance transport of loess. The loess/palaeosol sequence of Harmignies is situated on a plateau called Cuesta d'Harmignies that slopes gently to the north. Thus, any reworking of wind-lain loess at this site would have been limited to local sheetwash or solifluction. Frechen et al. (2001a) provided a more recent detailed description of the section, which is summarized below.

A truncated palaeosol occurs within various facies according to the source material and is thought to correlate with the last interglacial period, OI sub-stage 5e. The Lower Weichselian can be subdivided into five sub-units, each representing significant climatic oscillations. Small frost cracks and an ice vein are contemporaneous and a thin calcareous loess layer was deposited. The palaeosols are grey brown podsolic soils and represent pedogenesis under a boreal climate. The initial aeolian accumulation was soil derived at first, mainly local and non-calcareous, but was followed successively by mixed material including long-distance calcareous loess, as evidenced by the distinctive mineralogy of the clay fraction. Arctic meadow soils developed synchronously below tundra vegetation.

During the Middle Weichselian, the loess was often reworked by solifluction and/or sheetwash. Three successive loess bodies contain intercalated tundra gley with frost cracks. An arctic meadow soil terminates this part of the record, and is correlated with the Moershoofd interstadial (Behre, 1989). The late stage of the Middle Weichselian was characterized by the deposition of loess alternating with erosion and re-deposition of sediments, large ice-wedge casts forming during that period. The sequence of the Middle Weichselian terminated with the formation of a well-developed palaeosol indicating a boreal climate with increased snow cover. The palaeosol is considered to be an equivalent of the Hengelo-Denekamp interstadial complex (Behre, 1989; Behre and van der Pflicht, 1992; Frechen et al., 2001a).

The Upper Weichselian can be subdivided into three parts. The first phase began with significant erosion and re-deposition of sediments reworked by slope wash and solifluction. The second part of the Upper Pleniglacial began with extreme aridity giving rise to dominant aeolian processes (very well-sorted loess) and thermal cracking but no ice-wedge formation. A short but important warming caused a deepening of the permafrost table, accompanied by solifluction and sheetwash, most likely comparable with the Nagelbeek-Kesselt complex (Haesaerts et al., 1981; Van Vliet-Lanoë, 1989, 1992). At Harmignies, the Last Glacial record terminates with a thick accumulation of loess with intercalated weakly developed cryosols. In the present climate of Svalbard, this soil-type forms in a few hundred years under prostrated tundra vegetation. The calcareous loess was truncated by sheet erosion, followed by weathering and formation of the Lateglacial surface soil. The section was again truncated by protohistorical soil erosion. In West Belgium, ice wedge activity during the Last Glaciation is confirmed by luminescence dating of loess covering the ice wedge horizon ("cooling down position") at the section at Harmignies. The abrupt short warm periods recorded in the sequence under study are related to Heinrich H3 and

H2 events, and so with ice surges and thinning of the ice sheet as well as a restored cyclonic circulation during summer in Western Europe (Van Vliet-Lanoë, 1996). As a consequence, flood activity in the outwash plains probably occurred in summer, in association with retrogressive ice-wedge degradation and loess/sand deposition in the late summer. As the thickening of the ice sheet induced high atmospheric pressures, stronger winds and drought, loess sedimentation proceeded continuously and very quickly from the onset of the cooling.

At the Kesselt section (site 2) in Belgian Limbourg, the Pleniglacial loess from below and above the Nagelbeek horizon has yielded TL age estimates ranging from 36 to 33 ka BP and from 22 to 20 ka BP, respectively (van den Haute et al., 1998). At Rocourt (site 4), Lateglacial loess gave TL age estimates ranging from 13.2 to 17.1 ka BP and Pleniglacial loess below the Eltville Tephra yielded a TL age of about 24.8 ka BP (Wintle, 1987). Haesaerts et al. (1999) investigated a detailed Upper Pleistocene loess/palaeosol sequence at Remicourt (site 3). There, Pleniglacial loess gave infrared stimulated luminescence (IRSL) age estimates between 18.7 and 25.8 ka BP (Frechen, unpublished).

In southeast England, loessic deposits were deposited between 18 and 13 ka BP in many sections along the southeast coast and the Thames valley. Wintle (1981) gave TL age estimates between 14.5 and 18.8 ka BP. Parks and Rendell (1992) determined TL age estimates ranging from 23 to 10 ka BP, as well as two older periods of accumulation between 125 and 50 ka BP and before 170 ka BP. The majority of the sites investigated yielded Upper Weichselian depositional ages, which can be correlated with OIS 2.

3. Central Europe

3.1. Rhineland

In the Rhineland, a truncated red brown forest soil correlates with the Last Interglacial Maximum indicating a deciduous forest during the Eemian. Owing to slope dynamics, the last interglacial sequence is more detailed at the Tönchesberg (site 25) and Koblenz-Metternich (site 19) than in other sections of the Rhineland. The Eemian interglacial soil is covered by a dark brown and red–brown palaeosol, each including an A horizon. At the section at Tönchesberg, reverse magnetization was determined within the pedosediments and correlated with the Blake event (about 117 ka BP), thus providing additional independent age control (Becker et al., 1989; Reinders and Hambach, 1995).

During the Lower Weichselian, several cycles of slope erosion and sediment accumulation (reworked sediment) occurred, as well as periods of soil formation. At the sections at Tönchesberg, there are four intercalated A horizons; the lowermost chernozem-like palaeosol is correlated with OI sub-stage 5c, the uppermost one, a chernozem-like palaeosol with strong clay illuviation, with OI sub-stage 5a (Boenigk and Frechen, 2001). These interstadial deposits underlie a thin loess layer, defined as a marker loess and interpreted by Kukla (pers. com.) as a Europe-wide dust storm caused by cooling at the boundary between Lower and Middle Weichselian (OI sub-stage 5a and OIS 4). This marker loess or its equivalent was described in a similar stratigraphic position in Alsace, the Rhineland, Bohemia and Moravia. The dust accumulation was followed by a period of erosion, as documented by a hiatus and/or a layer of pellet sands in many Central European loess regions. In the Rhineland, the pedosediments underwent at least two periods of soil formation, as documented by two weak A horizons.

In the early part of the Middle Weichselian, which is correlated with OIS 3 of the deep-sea record, periods of weak soil formation occurred, as evidenced by A horizons. The sequence documenting the period between 59 and about 40 ka is poorly preserved in a few sections only because a major period of erosion occurred prior to 40 ka BP. A period of loess accumulation between 40 and 25 ka BP was interrupted by two periods of soil formation in the section at Tönchesberg (site 25). At the section at Remagen-Schwalbenberg (site 23), near the confluence of the Rhine and Ahr rivers, the Middle Weichselian is characterized by loess and reworked loess with six intercalated weak soils that formed in the time period from 45 to 25 ka BP.

During the Upper Weichselian, two main periods of loess accumulation occurred (24–20 ka BP and 17–13 ka), as is shown in the exposed section at Koblenz-Metternich (site 19) (Frechen et al., 1995). A significant period of surface destabilization occurred at about 17 ka, as indicated in Belgium and the Netherlands by the Beuningen gravel bed and also in the Rhineland by a significant hiatus in many loess sections (Frechen, 1992; Frechen et al., 2001b; Frechen and van den Berg, 2002). The event decreased in intensity towards the more continental environments further east. Owing to this period of surface destabilization, the Pleniglacial loess is not preserved. Lateglacial loess, however, is exposed in most of the sections under investigation (e.g. Tönchesberg (site 25), Wannenköpfe (site 27), Schweinskopf (site 24) etc.).

In the northern part of the Rhineland (Lower Rhine area), the Last Glacial loess record is less complete than in the southern part (Middle Rhine area). The Upper Weichselian loess has a thickness up to 13.50 m on leeward slopes and contains numerous intercalated cryosols. However, most of the loess has been reworked and re-deposited by slope wash or solifluction, as shown in the sections at Grafenberg (site 17) and Garzweiler-Süd 38 (site 16) (Henze, 1998). IRSL dating yielded Lateglacial depositional ages for both sites (Frechen in Henze, 1998).

3.2. Southern Germany and Alsace

A truncated Bt horizon of a brown forest soil is correlated with the Eemian interglacial period in Southern Germany and Alsace, e.g. at the sections at Nußloch (Nussloch: site 21), Böckingen (site 12), Bönnigheim (sites 13 and 14) and Achenheim (site 5) (Rousseau et al., 1998; Frechen, 1999a; Antoine et al., 2001). A detailed Lower Weichselian loess-palaeosol record is exposed at several sites in the Mainz basin. The Mainz-Weisenau section (site 20) contains three steppe and/or forest steppe soils. The middle and uppermost humic-rich are correlated with Lower Weichselian interstadials.

At the Nußloch section (site 21) near Heidelberg, Germany, the Middle Weichselian has a thickness of 2–4 m. The loess has intercalated palaeosols, a lower and upper cambisol horizon, a gley and two tundra gley horizons. Similar sequences have been described from the Neckar-Main area (Bibus, 1989; Frechen et al., 1999).

The Upper Weichselian record has a thickness of 10–12 m at the Nußloch section (Antoine et al., 1999; Lang et al., 2003). Typical calcareous loess without traces of weathering is exposed. The single loess units have a thickness of 0.5 to 2.0 m and have intercalated tundra gleys (gelic gleysols). The tundra gleys result from hydromorphic conditions showing slight decalcification with redistribution of carbonates at the base of the profile (carbonate concretions), reduction and redistribution of iron (oxidized patches and bands), as well as slight enrichment in organic carbon (more intense rooting and biological activity). The snail fauna is represented mainly by species of open environments. Tundra gleys represent short periods of strong reduction or cessation of loess sedimentation reflecting a very cold and locally more humid environment with the development of permafrost (cryo-injections) and local cracks with ice-wedges. The Pleniglacial and Lateglacial tundra gleys are exposed in most of the profiles in northwestern and central Europe. At the Bobingen section (site 11) near the Alpine Wertach and Lech rivers, the Upper Weichselian loess is richer in sand owing to its proximity to the sediment source and the glaciated area (Becker-Haumann and Frechen, 1997).

3.3. Austria, Czech Republic, Slovakia

The Last Interglacial/Glacial loess record of Austria, the Czech Republic and Slovakia is similar to that for the Rhineland and Southern Germany, indicating similar climatic conditions during the past 130,000 years. A truncated brown forest soil, the remnant of the Eemian interglacial, is covered by at least three chernozems or chernozem-like palaeosols (Musson and Wintle, 1994; Zöller et al., 1994; Frechen et al., 1999). The two upper palaeosols are developed in loess or loess-like sediments, indicating periods of aeolian accumulation during the Lower Weichselian. The chronostratigraphic position of the uppermost chernozem is still uncertain, but a Middle or Lower Weichselian age seems likely (Frechen et al., 1999). This palaeosol is covered by loess, which is in turn capped by a weak soil, indicating the termination of the Middle Weichselian. It is likely that part of the Middle Weichselian loess record is missing in the section under study. The youngest sediment consists of Pleniglacial and Lateglacial loess capped by a Holocene soil, as exposed in Lower Austria (Zöller et al., 1994), Upper Austria (Terhorst et al., 2002), and the Czech Republic (Musson and Wintle, 1994; Zöller et al., 1994; Frechen et al., 1999; Zander, 1999, 2000).

4. Southeast Europe

4.1. Hungary

In Hungary, the major loess source is the Danube River and its tributaries. The Upper Pleistocene loess record is different from the previously described loess areas in Europe and so correlations with loess sequences in Austria and Moravia are difficult. The Eemian interglacial soil, a forest-steppe chernozem-like palaeosol called MF2 in the Hungarian stratigraphy (Wintle and Packman, 1988; Zöller et al., 1994; Oches and McCoy, 1995; Frechen et al., 1997) is formed in loess that dates from the penultimate glacial period. This palaeosol is covered by Middle Weichselian loess. Either large discontinuities developed above the MF2 palaeosol, indicating that most of the record of the Lower Weichselian is not exposed, or a very low aeolian accumulation rate occurred during this period. The Middle Weichselian loess and sandy loess is overlain by a second forest-steppe chernozem-like palaeosol called MF1 in the Hungarian stratigraphy, which formed later during the Middle Weichselian (Novothny et al., 2002). Loess accumulated again during the upper part of the Middle Weichselian and was followed by weak soil formation, as evidenced by a humic-rich horizon called "h2" in the Hungarian stratigraphy. The "h2" horizon most likely correlates with the Denekamp interstadial of the NW European stratigraphy. The uppermost loess is correlated with OIS 2 and contains a humic-rich zone called the "h1" horizon. The "h1" horizon most likely formed between 19 and 17 ka BP.

4.2. Serbia, Romania, Bulgaria

In the lower Danube basin, loess accumulated on plateau uplands and fluvial terraces through Serbia, into Bulgaria and Romania. Thick loess with several intercalated palaeosols is well exposed along the Black Sea coast. The tendency for present-day precipitation totals to decrease eastwards is evident in the palaeoclimatic precipitation gradient as indicated by the palaeosols. The most recent interpretations of palaeosol ages in Serbia are based on amino acid geochronology (Markovic et al., 2003a), with luminescence dating in progress. In the loess section at Ruma, Serbia, the last interglacial palaeosol, S1, which correlates with palaeosol F2 of Bronger and Heinkele (1989), is a series of three superposed chernozems overlain by loess correlated with OIS 4 of the deep-sea record (Markovic et al., 2003a, b). The Middle Weichselian (OIS 3) is represented in the region by a weakly developed chernozem soil, reflecting slightly warmer and drier conditions during that interval than inferred from PK1 or the Stillfried-B palaeosol (Kukla, 1977) in Czech Republic and Austria, respectively. In many Serbian loess profiles the OIS 3 palaeosol is absent. In general, the maximum thickness of Upper Pleistocene loess and palaeosols ranges from 5–10 m. Reliable numerical age estimates are not currently available from loess records from this region, making accurate estimation of loess accumulation rates impossible.

Loess deposits in Bulgaria and Romania occur mainly along the lower Danube valley and Black Sea coast. Loess and palaeosols have been less extensively studied here than elsewhere in central and Eastern Europe, with limited numerical age estimates available for determining mass accumulation rates. The magnetic susceptibility of Middle and Upper Pleistocene loess and palaeosols in this region has been correlated with the marine oxygen-isotope record and supports the interpretation that the first well developed chernozem below the Holocene soil is the last interglacial palaeosol, designated S1 (Jordanova and Petersen, 1999a b,; Panaiotu et al., 2001). Upper Pleistocene loess is not well subdivided, lacking a clear Middle Weichselian palaeosol or other regional marker horizons within the Last Glacial loess. The Holocene climatic regime and steppe vegetation have resulted in the formation of chernozems. Similar environmental conditions are indicated by palaeosol S1, which is also described as a chernozem. The most thoroughly studied section in Bulgaria is the Koriten profile (Jordanova and Petersen, 1999a, b), which contains seven loess units and six interglacial palaeosols. Total thickness of the Upper Pleistocene section, including S1, L1, and S0, reaches a maximum of about 8 m.

5. Eastern Europe

5.1. Russian plain

Loess-palaeosol formations of the eastern European plains of Russia and Ukraine are among the most extensive loess-covered landscapes in the world between 44–56°N and 24–50°E. Given such a great extent of loess, the character and thickness of individual loess units and palaeosols can vary significantly. Numerous loess profiles have been investigated here, with an extensive review of the stratigraphy and geochronology of loess-palaeosol formations of the Russian Plain provided by Velichko (1990).

The Mezin soil complex forms the base of the Upper Pleistocene section. It begins with the basal interglacial forest palaeosol, the Salyn soil, corresponding to OI substage 5e. A thin loess separates this unit from the overlying Krutitsy soil, which is a late OIS 5 chernozem. This palaeosol complex is rather uniform across the region and correlates with PK3 in Czech Republic, MF2 in Hungary, the Stillfried-A in Austria, and the Rocourt soil in Belgium.

Deposition of glacial period loess began with the relatively thin Khotylevo Loess, commonly only a couple of metres thick. Developed in the upper part of this loess is the interstadial Bryansk soil, with radiocarbon age estimates placing soil formation at between 32 and 24 ka BP. (Velichko, 1990). Three additional loess units, separated by two weak tundra-gley palaeosols, complete the Upper Pleistocene section. These upper palaeosols and loess units contain cryogenic features, including ice-wedge pseudomorphs and other permafrost indicators. At the Likhvin section, Little et al. (2002) reported luminescence age estimates ranging from 23 ± 1 ka to 24 ± 2 ka BP for Pleniglacial loess overlying the Bryansk palaeosol.

5.2. Ukraine

The most complete and Upper Pleistocene loess sequences in Ukraine, and those sub-divided in the greatest detail, are found throughout the Dnieper Plain, especially along the upper and middle Dnieper River valley. The subdivision of last interglacial–glacial stratigraphy in the region is broadly similar to that described for the Czech Republic and Slovakia. Although many tens of sections have been described in the literature (summarized by Veklich, 1979; Veklich and Sirenko, 1984), excellent examples of nearly complete representative sections were recently described from Vyazovok, near the town of Lubny (Rousseau et al., 2001) and Stari Bezradychy, near Kiev (Gerasimenko, 2001). The last interglacial palaeosol complex overlies either till or loess of the Dnieper glaciation. The Kaydaky soil complex, with sub-horizons ranging from boreal brown soils to leached chernozems and grey forest soils, marks OI sub-stage 5e. Relatively thin (0.2–1.0 m) Tyasmin loess separates the Kaydaky soil from the overlying Pryluky soil complex, which commonly has sub-units ranging from a weak meadow soil to a brown forest soil, ending with a chernozem. Above this lies the Uday loess, with an average thickness of about 3 m; this unit is overlain by the Vytachiv soil complex, an OIS 3 interstadial series of two or three cambisols and frost-gley soils. The Bug loess, which may be up to 15 m thick, is the thickest Upper Pleistocene loess and was deposited during OIS 2. The weakly developed chernozem-like Dofinivka soil complex developed under cool, arid conditions. Prychernomorsk loess represents the latest OIS 2 loess accumulation, with the Holocene soil formed in the uppermost part. Together, the Bug and Prychernomorsk loess represent the highest rates of loess accumulation in the section, although confident numerical age estimates are required to quantify rates for comparison with other regions described in this paper.

6. Methods of calculating mass accumulation rates (MARs)

For this study, we have compiled information from 43 loess sections, for which detailed and reliable chronological information is available (Table 1; Fig. 2). The highest density of sites is located along the large fluvial systems of the Rhine (Germany) and the Danube (Austria and Hungary) rivers. In contrast to Central Asia and China, areas with relatively stable depositional environments are rare in Europe and so continuous loess records are based on composite sections in many places. Thus, the choice of reliable dating methods and reliable age estimates is obviously critical in compiling a reliable stratigraphic record (Table 2).

The sites were classified according to their geomorphological setting owing to the influence of landscape on continuity and thickness of loess deposits. In this paper we distinguish three main geomorphic settings, including plateau, slope and terrace positions. Plateaus are relatively stable settings and are therefore likely to experience more continuous deposition and less sediment reworking (e.g. Harmignies). However, erosion processes such as deflation, solifluction, cryoturbation and sheet wash can also occur at plateau sites, resulting in discontinuous records. Only six of the 43 sites considered in this study were classified as plateau sites (i.e. Albertirsa (site 39), Harmignies (site 1), Kärlich (site 18), Mende (site 40), Nußloch (site 21), and Saint Romain (site 8)). Twenty-three of the 43 sites considered are classified as terrace sites, where loess was deposited on a river terrace. These sites are proximal to local dust sources that may result in enhanced depositional rates compared to other loess sites. Loess deposits on both gentle and steep slopes are likely to be subject to reworking; consequently pure loess is seldom found and unconformities are common. One section (Sables d'Or les Pins (site 6)) is classified as a marine shore cliff, and is currently located on a cliff in Brittany, France. At the time of loess accumulation, when sea level was significantly lower than today (e.g. both the Pleniglacial and Lateglacial), this site was located on a wide plain.

In this paper we distinguish three material types (Fig. 3):

a. *Loess*: primary (or direct airfall) loess: a mainly uniform or weakly stratified, yellowish brown, highly porous, calcareous silt, which sometimes shows some evidence for syndepositional reworking by surface wash.
b. *Partially reworked loess*: primary aeolian loess, which has been reworked by running water or slope processes, stratified.
c. *Layered, reworked loess with solifluction* (*slope wash*): reworked loess, which has undergone slope wash or solifluction; includes weathered decalcified loess.

The chronological framework is obviously critical for the correlation of synchronously deposited loess and the MAR calculation. The most commonly used numerical dating methods in loess research for the last interglacial/glacial cycle are luminescence and radiocarbon, with amino acid racemization being used as a relative dating tool. Loess and loess-like sediments are particularly suitable for the application of luminescence dating techniques, which measure the time that has elapsed since the last exposure to sunlight (Wintle, 1997). In order to minimize inter-laboratory errors in luminescence dating owing to different laboratory treatments, most of the sites taken into account in this study are those investigated by Frechen and co-workers during the past 15 years. A few other sites, for which chronological cross-checks were available, were also used, mainly those localities studied by Wintle and co-workers and Lang, Zöller and their co-workers. Luminescence age estimates appear to be reliable for the time period 28–13 ka BP. However, in Eastern Europe, many records were excluded from MAR calculations because they lacked adequate thermoluminescence dating or because their documentation in the original publication is inadequate (cf. Wintle and Huntley, 1982).

Radiocarbon dating has been widely used on charcoal and bones from the past 28,000 years. In this study, calibrated radiocarbon ages (mainly AMS ^{14}C) were used in addition to the luminescence ages at a few sites, such as Nußloch (site 21) in Germany or Grubgraben (site 32) in Austria.

Table 1
Site information and mass accumulation rates

Location no.	Locality name	Country	Latitude (deg)	Longitude	Geomorphic setting	Last glacial loess thickness (m)	Material dated	MAR[a], 13–18 ka	MAR, 18–28 ka	Reference
1	Harmignies	Belgium	50.41	4.02	Plateau	5.00	Loess		1467–3135	Frechen et al. (2001a)
2	Kesselt	Belgium	50.84	5.60	Slope	4.70	Reworked loess		330–825	Van den Haute et al. (1998)
3	Remicourt	Belgium	50.67	5.40	Gentle slope	4.00	Loess		453	Frechen, unpublished
4	Rocourt	Belgium	50.68	5.54	Terrace	3.00	Loess		93	Wintle (1987)
5	Achenheim	France	48.35	7.38	Gentle slope	3.00	Loess		257	Rousseau et al. (1998)
6	Sables d'Or les Pins	France	48.65	2.39	Marine shore cliff	3.50	Reworked loess	261	354	Monnier et al. (1997) Engelmann and Frechen (1998)
7	Saint Sauflieu	France	49.79	2.25						Wintle et al. (1984)
8	Saint-Romain	France	49.54	0.36	Plateau	1.80	Loess	608		Locht et al. (2003)
9	Villiers-Adam	France	49.06	2.20	Slope	10.20				Radtke et al. (1998)
10	Am Bingert, Wiesbaden	Germany	50.12	8.28	Slope	4.20	Reworked loess	1591	361	
11	Bobingen	Germany								Becker-Haumann and Frechen (1997)
12	Böckingen	Germany	49.13	9.18	Terrace	2.50	Loess	330	3300	Frechen (1999a)
13	Bönnigheim A	Germany	49.04	9.14	Terrace	2.80	Loess		131	Frechen (1999a)
14	Bönnigheim B	Germany	49.04	9.14	Terrace	5.20	Loess	2750	283–1500	Frechen (1999a)
15	Elsbachtal	Germany	51.08	6.52	Terrace	4.40	Reworked loess	528–3575		Frechen et al. (2003)
16	Garzweiler-Süd38	Germany	51.07	6.52	Terrace	6.00	Reworked loess	1467		Henze (1998)
17	Grafenberg	Germany	51.30	6.80	Leeward slope	13.50	Reworked loess	3345		Henze (1998)
18	Kärlich	Germany	50.39	7.48	Plateau	1.90	Loess			Wintle (1985)
19	Koblenz-Metternich	Germany	50.37	7.55	Slope	9.50	Loess	679		Frechen et al. (1995)
20	Mainz-Weisenau	Germany	49.99	8.28	Slope		Loess			Frechen and Preusser (1995)
21	Nussloch	Germany	49.30	8.80	Plateau	11.30	Loess, loess organic matter		1213–6129	Lang et al. (2003)
22	Ockenfels	Germany				9.50	Loess			Preusser and Frechen (1999)
23	Schwalbenberg	Germany	50.57	7.24	Terrace	3.10	Loess	990		Frechen, unpublished; Zöller et al. (1991)
24	Schweinskopf	Germany	50.36	7.42	Crater slope	1.30	Loess			Frechen (1999c)
25	Tönchesberg	Germany	50.35	7.35	Crater slope	1.90	Loess	518–1980		Frechen (1992)
26	Wallertheim	Germany			Terrace		Loess			Wintle and Brunnacker (1982)
27	Wannenköpfe	Germany	50.37	7.39						Frechen and Justus (1998)
28	Dolní Věstonice	Czech Republic	48.89	16.66	Terrace slope	5.80	Loess, charcoal	2625–3712	754–1100	Damblon et al. (1996), Frechen et al. (1999)
29	Kutná Hora	Czech Republic	49.95	15.26	Terrace	4.20	Loess			Frechen et al. (1999)
30	Zemechy	Czech Republic	50.23	14.22	Terrace	4.40	Loess	786		Zander (1999)
31	Altheim	Austria	48.25	13.24	Terrace	2.00	Reworked loess			Terhorst et al. (2002)
32	Grubgraben	Austria	48.50	15.80	Terrace	7.00	Loess	900	2100	Damblon et al. (1996)
33	Gunderding	Austria	48.26	13.23	Terrace	3.50	Reworked loess	880–19800		Terhorst et al. (2002)
34	Stillfried	Austria	48.42	16.84	Terrace	2.00	Reworked loess		229	Zöller et al. (1994)
35	Stratzing	Austria	48.45	15.59	Terrace	1.30	Reworked loess			Zöller et al. (1994)
36	Trindorf	Austria	48.24	14.14	Terrace	2.50	Reworked loess		2970	Terhorst et al. (2002)
37	Wels	Austria	48.17	14.02	Terrace	2.00	Reworked loess			Zöller et al. (1994)
38	Willendorf II	Austria	47.79	16.05	Terrace	3.20	Loess		372–886	Damblon et al. (1996)
39	Albertirsa	Hungary	47.24	19.61	Loess plateau	3.50	Loess		841	Novothny et al. (2002)
40	Mende	Hungary	47.42	19.44	Loess plateau	4.30	Loess, charcoal		519	Frechen et al. (1997), Pécsi (1991), Wintle and Packman (1988)
41	Paks	Hungary	46.62	18.85	Terrace slope (Danube)	6.00	Loess	1317–4007		Frechen et al. (1997)
42	Cosaoutsi, Moldavia	Romania			West bank, Diepr	14.00	Reworked loess	2979	11,786	Damblon et al. (1996)
43	Mituc Malu Galben	Romania				6.65	Reworked loess		1102	Damblon et al. (1996)

Range of values indicate range of possible estimates of MAR based on the scatter in the dates.
[a] MAR = Mass accumulation rate.

Table 2
Dating information for last glacial loess

Location no.	Locality name	Depth below modern soil (m)	Lab-number	Material dated	Dating methods available	Method	Age (ka)	SD	Comments
5	Achenheim	0.90	1	Loess		TL-REGEN	17	2.5	
5	Achenheim	1.80	2	Loess		TL-REGEN	19.5	1.6	
5	Achenheim	2.50	3	Loess		TL-REGEN	24	2.7	
39	Albertirsa	0.30	HCB17	Loess	1,3,10	IRSL-ADD	20.6	4.9	
39	Albertirsa	0.60	HCB16	Loess	1,3,10	IRSL-ADD	16.8	4.8	
39	Albertirsa	0.90	HCB15	Loess	1,3,10	IRSL-ADD	19.2	2.2	
39	Albertirsa	1.50	HCB14	Loess	1,3,10	IRSL-ADD	21.7	4.8	
39	Albertirsa	1.80	HCB13	Loess	1,3,10	IRSL-ADD	21.9	2	
39	Albertirsa	2.10	HCB12	Loess	1,3,10	IRSL-ADD	24.4	3	
39	Albertirsa	2.60	HCB11	Loess	1,3,10	IRSL-ADD	18.2	3.3	
39	Albertirsa	2.90	HCB10	Loess	1,3,10	IRSL-ADD	22.9	2.9	
31	Altheim	1.40	Alt 1	Reworked loess	1,3,10	IRSL-ADD	29.8	2.4	
31	Altheim	1.90	Alt 2	Reworked loess	1,3,10	IRSL-ADD	22.6	3.3	
10	Am Bingert, Wiesbaden	0.50	AB1	Reworked loess	1,2,3,4,6	IRSL-ADD	13.6	2.7	
10	Am Bingert, Wiesbaden	1.20	AB2	Reworked loess	1,2,3,4,6	IRSL-ADD	13.3	2.8	
10	Am Bingert, Wiesbaden	1.70	AB3	Reworked loess	1,2,3,4,6	IRSL-ADD	13.6	3.3	
10	Am Bingert, Wiesbaden	2.00	AB4	Reworked loess	1,2,3,4,6	IRSL-ADD	14	1.8	
10	Am Bingert, Wiesbaden	2.20	AB5	Reworked loess	1,2,3,4,6	IRSL-ADD	15.6	2.4	
10	Am Bingert, Wiesbaden	2.70	AB6	Reworked loess	1,2,3,4,6	IRSL-ADD	19.6	3.6	
10	Am Bingert, Wiesbaden	3.00	AB7	Reworked loess	1,2,3,4,6	IRSL-ADD	12.9	2.3	
10	Am Bingert, Wiesbaden	3.20	AB8	Reworked loess	1,2,3,4,6	IRSL-ADD	16.4	2.8	
10	Am Bingert, Wiesbaden	3.50	AB9	Reworked loess	1,2,3,4,6	IRSL-ADD	19.4	3.5	
10	Am Bingert, Wiesbaden	3.70	AB10	Reworked loess	1,2,3,4,6	IRSL-ADD	21.4	3.7	
10	Am Bingert, Wiesbaden	4.00	AB11	Reworked loess	1,2,3,4,6	IRSL-ADD	20.7	4.9	
11	Bobingen	0.25	Bob13	Loess	1,2,3,4	IRSL-REGEN	17.6	1.9	
11	Bobingen	0.75	Bob12	Loess	1,2,3,4	IRSL-REGEN	24.7	3.8	
11	Bobingen	1.30	Bob11	Loess	1,2,3,4	IRSL-REGEN	19.2	2.8	
11	Bobingen	1.75	Bob10	Loess	1,2,3,4	IRSL-REGEN	18.9	3.3	
11	Bobingen	2.00	Bob9	Loess	1,2,3,4	IRSL-REGEN	21.5	3.8	
11	Bobingen	2.30	Bob8	Loess	1,2,3,4	IRSL-REGEN	16.7	2.6	
11	Bobingen	2.70	Bob7	Loess	1,2,3,4	IRSL-REGEN	23.9	3.1	
12	Böckingen	0.20	BK46	Loess	1,2,3,4	IRSL-ADD	15.4	2.4	
12	Böckingen	0.40	BK45	Loess	1,2,3,4	IRSL-ADD	15.2	1.4	
12	Böckingen	0.60	BK44	Loess	1,2,3,4	IRSL-ADD	17.9	2.3	
12	Böckingen	0.80	BK43	Loess	1,2,3,4	IRSL-ADD	18.4	3.5	
12	Böckingen	1.00	BK42	Loess	1,2,3,4	IRSL-ADD	18.1	1.9	
12	Böckingen	1.20	BK41	Loess	1,2,3,4	IRSL-ADD	20.9	2.1	
12	Böckingen	1.40	BK40	Loess	1,2,3,4	IRSL-ADD	20.9	3.1	
12	Böckingen	1.60	BK39	Loess	1,2,3,4	IRSL-ADD			
12	Böckingen	1.80	BK38	Loess	1,2,3,4	IRSL-ADD	16.2	1.7	
12	Böckingen	2.00	BK37	Loess	1,2,3,4	IRSL-ADD			
12	Böckingen	2.20	NK36	Loess	1,2,3,4	IRSL-ADD	20.2	2.8	
12	Böckingen	2.40	BK35	Loess	1,2,3,4	IRSL-ADD	22.9	2	
13	Bönnigheim A	0.30	Bö22	Loess	1,2,3,4	IRSL-ADD			

13	Bönnigheim A	1.20	Bö21	Loess	1,2,3,4	IRSL-ADD	17.5	2.8	
13	Bönnigheim A	1.70	Bö20	Loess	1,2,3,4	IRSL-ADD	23.8	3.4	
14	Bönnigheim B	2.10	Bö32	Loess	1,2,3,4	IRSL-ADD	15.7	1.5	
14	Bönnigheim B	3.10	Bö31	Loess	1,2,3,4	IRSL-ADD	16.3	1.8	
14	Bönnigheim B	4.10	Bö30	Loess	1,2,3,4	IRSL-ADD	27.7	3.1	
14	Bönnigheim B	4.50	Bö29	Loess	1,2,3,4	IRSL-ADD	22.6	4.2	
14	Bönnigheim B	4.80	Bö28	Loess	1,2,3,4	IRSL-ADD	22.9	3.7	
14	Bönnigheim B	5.10	Bö27	Loess	1,2,3,4	IRSL-ADD	26.1	2.4	
42	Cosaoutsi	8.10	GrN-21792	Reworked loess		14C	17.23	0.14	
42	Cosaoutsi	8.50	GrN-21793	Reworked loess		14C	17.62	0.21	
42	Cosaoutsi	8.90	GrN-21360	Reworked loess		14C	17.91	0.08	
42	Cosaoutsi	8.90	GrN-21359	Reworked loess		14C	18.03	0.15	
42	Cosaoutsi	9.40	GrN-21794	Reworked loess		14C	17.95	0.1	
42	Cosaoutsi	10.00	GrN-21361	Reworked loess		14C	19.2	0.13	
42	Cosaoutsi	11.50	GrN-21795	Reworked loess		14C	19.41	0.1	
28	Dolní Věstonice	0.50	DV17	Loess	1,2,3,4,5,10,12	IRSL-REGEN	17.5	1.7	Frechen et al. (1999)
28	Dolní Věstonice	1.00	DV15	Loess	1,2,3,4,5,10,12	IRSL-REGEN	14.8	1.8	Frechen et al. (1999)
28	Dolní Věstonice	1.30	DV12	Loess	1,2,3,4,5,10,12	IRSL-REGEN	15.2	1.5	Frechen et al. (1999)
28	Dolní Věstonice	2.70	DV11	Loess	1,2,3,4,5,10,12	IRSL-REGEN	14.8	1.5	Frechen et al. (1999)
28	Dolní Věstonice	3.00	GrN2102	Charcoal	1,2,3,4,5,10,12	14C	15.35	1	Uncalibrated, Damblon et al. (1996)
28	Dolní Věstonice	3.70	DV10	Loess	1,2,3,4,5,10,12	IRSL-REGEN	15.8	1.5	Frechen et al. (1999)
28	Dolní Věstonice	4.00	GrN2093	Charcoal	1,2,3,4,5,10,12	14C	18.4	0.7	Uncalibrated, Damblon et al. (1996)
28	Dolní Věstonice	4.20	DV14	Loess	1,2,3,4,5,10,12	IRSL-REGEN	19.6	2.3	Frechen et al. (1999)
28	Dolní Věstonice	5.00	a	Charcoal	1,2,3,4,5,10,12	14C	19.7	1.6	Damblon et al. (1996)
28	Dolní Věstonice	5.60	DV9	Loess	1,2,3,4,5,10,12	IRSL-REGEN	22.6	2.4	Frechen et al. (1999)
28	Dolní Věstonice	5.70	b	Charcoal	1,2,3,4,5,10,12	14C	21.6	1.9	Damblon et al. (1996)
28	Dolní Věstonice	5.80	DV8	Loess	1,2,3,4,5,10,12	IRSL-REGEN	23.1	2.3	Frechen et al. (1999)
28	Dolní Věstonice	5.80	c	Charcoal	1,2,3,4,5,10,12	14C	17.5	1.7	Damblon et al. (1996)
15	Elsbachtal	2.20	GAR7	Reworked loess	1,2,3,4,5	IRSL-ADD	16.5	1.5	
15	Elsbachtal	2.70	GAR6	Reworked loess	1,2,3,4,5	IRSL-ADD	14.6	2.2	
15	Elsbachtal	3.20	GAR5	Reworked loess	1,2,3,4,5	IRSL-ADD	16.2	1.7	
15	Elsbachtal	3.50	GAR4	Reworked loess	1,2,3,4,5	IRSL-ADD	17.1	1.6	
15	Elsbachtal	4.00	GAR3	Reworked loess	1,2,3,4,5	IRSL-ADD	19.7	2.1	
16	Garzweiler-Süd38	1.80	GS14	Reworked loess	1,2,3,4,10	IRSL-ADD	12.7	3.4	
16	Garzweiler-Süd38	3.00	GS13	Reworked loess	1,2,3,4,10	IRSL-ADD	13.4	1.3	
16	Garzweiler-Süd38	4.00	GS12	Reworked loess	1,2,3,4,10	IRSL-ADD	15.6	1.5	
16	Garzweiler-Süd38	5.00	GS11	Reworked loess	1,2,3,4,10	IRSL-ADD	15.8	2.2	
16	Garzweiler-Süd38	6.00	GS10	Reworked loess	1,2,3,4,10	IRSL-ADD	13.6	1.5	
17	Grafenberg	2.50	GRA16	Reworked loess	1,2,3,4,10	IRSL-ADD	15	1.5	
17	Grafenberg	3.00	GRA15	Reworked loess	1,2,3,4,10	IRSL-ADD	13.4	1.2	
17	Grafenberg	3.50	GRA14	Reworked loess	1,2,3,4,10	IRSL-ADD	14.9	1.2	
17	Grafenberg	4.70	GRA13	Reworked loess	1,2,3,4,10	IRSL-ADD	13.6	1.4	
17	Grafenberg	5.20	GRA12	Reworked loess	1,2,3,4,10	IRSL-ADD	16.8	1.8	
17	Grafenberg	5.70	GRA11	Reworked loess	1,2,3,4,10	IRSL-ADD	18.3	3.3	
17	Grafenberg	6.70	GRA10	Reworked loess	1,2,3,4,10	IRSL-ADD	16.3	1.9	
17	Grafenberg	6.90	GRA9	Reworked loess	1,2,3,4,10	IRSL-ADD	13.6	2.6	
17	Grafenberg	7.50	GRA8	Reworked loess	1,2,3,4,10	IRSL-ADD	13.4	1.9	
17	Grafenberg	8.50	GRA7	Reworked loess	1,2,3,4,10	IRSL-ADD	14.4	2.4	

Table 2 (*continued*)

Location no.	Locality name	Depth below modern soil (m)	Lab-number	Material dated	Dating methods available	Method	Age (ka)	SD	Comments
17	Grafenberg	9.50	GRA6	Reworked loess	1,2,3,4,10	IRSL-ADD	14.6	1.8	
17	Grafenberg	10.40	GRA5	Reworked loess	1,2,3,4,10	IRSL-ADD	13.8	3.2	
17	Grafenberg	10.50	GRA4	Reworked loess	1,2,3,4,10	IRSL-ADD	18	3.9	
17	Grafenberg	11.00	GRA3	Reworked loess	1,2,3,4,10	IRSL-ADD	18.6	3	
17	Grafenberg	11.50	GRA2	Reworked loess	1,2,3,4,10	IRSL-REGEN	13	1.8	
17	Grafenberg	13.00	GRA1	Reworked loess	1,2,3,4,10	IRSL-REGEN	21.9	2.9	
32	Grubgraben	6.50	AL1	Bones	5,10	14C	16.8	0.28	
32	Grubgraben	6.80	AL2a	Bones	5,10	14C	18.07	0.27	
32	Grubgraben	6.80	AL2b	Bones	5,10	14C	17.35	0.19	
32	Grubgraben	7.50	AL3	Bones	5,10	14C	18.62	0.22	
33	Gunderding	0.40	GUN 1	Reworked loess	1,3,10	IRSL-ADD	14.2	1.2	
33	Gunderding	1.20	GUN 2	Reworked loess	1,3,10	IRSL-ADD	15.7	1.6	
33	Gunderding	2.80	GUN 3	Reworked loess	1,3,10	IRSL-ADD	14.4	1.1	
1	Harmignies	1.40	HAR1	Loess	1,2,3,4,10	IRSL-ADD	22	3.3	
1	Harmignies	1.60	HAR2	Loess	1,2,3,4,10	IRSL-ADD	16.9	2.3	
1	Harmignies	1.80	HAR3	Loess	1,2,3,4,10	IRSL-ADD	21.4	3.5	
1	Harmignies	2.30	HAR4	Loess	1,2,3,4,10	IRSL-ADD	21.5	3.3	
1	Harmignies	2.40	HAR5	Loess	1,2,3,4,10	IRSL-ADD	19.8	3	
1	Harmignies	2.80	HAR6	Loess	1,2,3,4,10	IRSL-ADD	21.8	3.8	
1	Harmignies	2.90	HAR7	Loess	1,2,3,4,10	IRSL-ADD	19.3	3	
1	Harmignies	3.00	HAR8	Loess	1,2,3,4,10				
1	Harmignies	3.10	HAR9	Loess	1,2,3,4,10	IRSL-ADD	20.3	2.6	
1	Harmignies	3.20	HAR10	Loess	1,2,3,4,10	IRSL-ADD	20.7	2.9	
1	Harmignies	3.30	HAR11	Loess	1,2,3,4,10	IRSL-ADD	23.6	3.7	
18	Kärlich	0.75		Loess	4,6,10	TL-REGEN	11.6	1.2	
18	Kärlich	1.25		Loess	4,6,10	TL-REGEN	13.9	1.5	
2	Kesselt	2.50		Reworked loess	4, 10	TL-ADD	19.8	1.6	
2	Kesselt	2.60		Reworked loess	4, 10	TL-ADD	18.5	2.6	
2	Kesselt	3.00		Reworked loess	4, 10	TL-ADD	20.7	1.6	
2	Kesselt	3.30		Reworked loess	4, 10	TL-ADD	25.2	3.1	
2	Kesselt	3.60		Reworked loess	4, 10	TL-ADD	19.9	2.1	
2	Kesselt	4.00		Reworked loess	4, 10	TL-ADD	17.6	2.3	
19	Koblenz-Metternich	0.40	MET35	Loess	1,2,3,4,6,7,10	IRSL-ADD	14.1	2.5	
19	Koblenz-Metternich	0.90	MET34	Loess	1,2,3,4,6,7,10	IRSL-ADD	16.3	2.5	
19	Koblenz-Metternich	1.30	MET33	Loess	1,2,3,4,6,7,10	IRSL-ADD	17	3.1	
19	Koblenz-Metternich	1.80	MET32	Loess	1,2,3,4,6,7,10	IRSL-ADD	17.5	3.1	
19	Koblenz-Metternich	2.30	MET31	Loess	1,2,3,4,6,7,10	IRSL-ADD	14.7	1.3	
19	Koblenz-Metternich	3.10	MET30	Reworked loess	1,2,3,4,6,7,10	IRSL-ADD	19.4	3.5	
19	Koblenz-Metternich	3.60	MET29	Loess	1,2,3,4,6,7,10	IRSL-ADD	19.1	2.1	
19	Koblenz-Metternich	4.20	MET28	Loess	1,2,3,4,6,7,10	IRSL-ADD	20.3	2.7	
19	Koblenz-Metternich	4.60	MET27	Loess	1,2,3,4,6,7,10	IRSL-ADD	14.8	2.3	
19	Koblenz-Metternich	5.00	MET26	Reworked loess	1,2,3,4,6,7,10	IRSL-ADD	25	5.8	
19	Koblenz-Metternich	5.70	MET25	Reworked loess	1,2,3,4,6,7,10	IRSL-ADD	17.5	2.2	
19	Koblenz-Metternich	6.50	MET24	Reworked loess	1,2,3,4,6,7,10	IRSL-ADD	20	4.8	
19	Koblenz-Metternich	7.50	MET23	Reworked loess	1,2,3,4,6,7,10	IRSL-ADD	16.8	3.3	

19	Koblenz-Metternich	7.95	MET22	Loess	1,2,3,4,6,7,10	IRSL-ADD	19.1	3.9	
19	Koblenz-Metternich	8.90	MET21	Reworked loess	1,2,3,4,6,7,10	IRSL-ADD	17.2	1.8	
29	Kutna Hora	2.30	KH6	Loess		IRSL-ADD	28.3	2.8	
29	Kutna Hora	2.60	KH5	Loess		IRSL-ADD	26.4	2.6	
29	Kutna Hora	3.50	KH4	Loess		IRSL-ADD	21.9	2.2	
29	Kutna Hora	4.00	KH3	Loess		IRSL-ADD	20.6	2.8	
20	Mainz-Weisenau	0.80	MW5	Loess	1,2,3,4,6,10	IRSL-ADD	19.4	3.2	
20	Mainz-Weisenau	3.80	MW11	Loess	1,2,3,4,6,10	IRSL-ADD	18.5	2	
20	Mainz-Weisenau	3.80	MW3	Loess	1,2,3,4,6,10	IRSL-ADD	17.8	2.6	
20	Mainz-Weisenau	3.80	MW11	Loess	1,2,3,4,6,10	IRSL-ADD	23	4.1	
20	Mainz-Weisenau	4.00	MW10	Loess	1,2,3,4,6,10	IRSL-ADD	16.3	3	
20	Mainz-Weisenau	4.00	MW4	Loess	1,2,3,4,6,10	IRSL-ADD	17.9	1.9	
20	Mainz-Weisenau	4.00	MW2	Loess	1,2,3,4,6,10	IRSL-ADD	19.4	1.9	
20	Mainz-Weisenau	4.90	MW6	Loess	1,2,3,4,6,10	IRSL-ADD	18.8	1.6	
20	Mainz-Weisenau	4.90	MW9	Loess	1,2,3,4,6,10	IRSL-ADD	17.9	2.5	
20	Mainz-Weisenau	5.10	MW7	Loess	1,2,3,4,6,10	IRSL-ADD	19.2	5.9	
20	Mainz-Weisenau	5.10	MW8	Loess	1,2,3,4,6,10	IRSL-ADD	20.1	1.6	
40	Mende	2.60	Hv1625	Charcoal	1,2,3,4,5,10	14C	16.8	1.6	Uncalibrated, Pécsi, 1991
40	Mende	4.40		Charcoal		14C	27	1.6	Uncalibrated, Pécsi, 1991
40	Mende	4.70		Loess		TL-REGEN	24	2	Wintle and Packman (1988)
40	Mende	4.80	Men13	Loess		IRSL-ADD	27	2.8	Frechen et al. (1997)
43	Mitic Malu Galben	3.36	GrA-5000	Reworked loess		AMS-C14	20.54	0.11	
43	Mitic Malu Galben	4.60	GrA-1353	Reworked loess		AMS-C14	23.85	0.1	
43	Mitic Malu Galben	5.05	GrN-20438	Reworked loess		C14	23.39	0.28	
43	Mitic Malu Galben	5.75	GrN-20439	Reworked loess		C14	23.99	0.25	
43	Mitic Malu Galben	6.60	GrN-20440	Reworked loess		C14	25.61	0.5	
43	Mitic Malu Galben	6.70	GrA-1020	Reworked loess		AMS-C14	24.07	0.18	
21	Nussloch	1.20	HDS 234	Loess	1,5,10	IRSL-ADD	19.8	2.2	
21	Nussloch	1.60	GifA-96221	Gastropod shell	1,5,10	AMS-14C	18.432	0.27	
21	Nussloch	2.10	HDS 235	Loess	1,5,10	IRSL-ADD	20.8	1.8	
21	Nussloch	2.80	HDS 236	Loess	1,5,10	IRSL-ADD	18.2	3.7	
21	Nussloch	3.00	GifA-99013	Loess organic matter	1,5,10	AMS-14C	21.695	0.564	
21	Nussloch	3.10	HDS 237	Loess	1,5,10	IRSL-ADD	19.5	2.3	
21	Nussloch	3.40	HDS 238	Loess	1,5,10	IRSL-ADD	19.2	1.7	
21	Nussloch	3.80	GifA-99014	Loess organic matter	1,5,10	AMS-14C	20.47	0.526	
21	Nussloch	4.20	HDS 239	Loess	1,5,10	IRSL-ADD	20.3	1.5	
21	Nussloch	4.80	HDS 240	Loess	1,5,10	IRSL-ADD	22.9	2.9	
21	Nussloch	5.00	GifA-99015	Loess organic matter	1,5,10	AMS-14C	22.925	0.975	
21	Nussloch	5.70	HDS 241	Loess	1,5,10	IRSL-ADD	20.2	2.4	
21	Nussloch	6.30	GifA-99016	Loess organic matter	1,5,10	AMS-14C	21.919	0.515	
21	Nussloch	6.40	HDS 242	Loess	1,5,10	IRSL-ADD	21.2	1.8	
21	Nussloch	7.00	GifA-99017	Loess organic matter	1,5,10	AMS-14C	22.55	1.115	
21	Nussloch	7.50	GifA-99018	Loess organic matter	1,5,10	AMS-14C	25.4	1	

Table 2 (*continued*)

Location no.	Locality name	Depth below modern soil (m)	Lab-number	Material dated	Dating methods available	Method	Age (ka)	SD	Comments
21	Nussloch	7.60	HDS 243	Loess	1,5,10	IRSL-ADD	19.6	2.4	
21	Nussloch	7.80	GifA-99019	Loess organic matter	1,5,10	AMS-14C	18.398	0.314	
21	Nussloch	8.60	HDS 244	Loess	1,5,10	IRSL-ADD	26	4	
21	Nussloch	9.00	GifA-98367	Loess organic matter	1,5,10	AMS-14C	27.5	1.6	
21	Nussloch	9.10	HDS 245	Loess	1,5,10	IRSL-ADD	24.8	4.1	
21	Nussloch	9.40	HDS 246	Loess	1,5,10	IRSL-ADD	23.2	2.4	
21	Nussloch	9.70	HDS 233	Loess	1,5,10	IRSL-ADD	24.8	4.7	
21	Nussloch	9.70	GifA-99020	Loess organic matter	1,5,10	AMS-14C	24.8	0.8	
21	Nussloch	11.10	GifA-99022	Loess organic matter	1,5,10	AMS-14C	29.25	2.05	
22	Ockenfels	0.90	OCK11	Reworked loess	1,2,3,4,6,10	IRSL-ADD	14.9	4.9	
22	Ockenfels	1.70	OCK10	Reworked loess	1,2,3,4,6,10	IRSL-ADD	13.8	1.5	
22	Ockenfels	2.60	OCK9	Reworked loess	1,2,3,4,6,10	IRSL-ADD	18.8	2.4	
22	Ockenfels	2.60	OCK8	Reworked loess	1,2,3,4,6,10	IRSL-ADD	16.5	2.2	
22	Ockenfels	3.00	OCK7	Reworked loess	1,2,3,4,6,10	IRSL-ADD	20.5	3.2	
22	Ockenfels	3.00	OCK6	Reworked loess	1,2,3,4,6,10	IRSL-ADD	17.3	1.8	
22	Ockenfels	3.80	OCK5	Reworked loess	1,2,3,4,6,10	IRSL-ADD	19.2	2	
22	Ockenfels	6.10	OCK4	Reworked loess	1,2,3,4,6,10	IRSL-ADD	19.7	2.2	
22	Ockenfels	6.85	OCK3	Reworked loess	1,2,3,4,6,10	IRSL-ADD	18.7	2	
22	Ockenfels	8.20	OCK2	Reworked loess	1,2,3,4,6,10	IRSL-ADD	21.1	5.4	
41	Paks	0.60	PAK1	Loess	1,2,3,4,10	IRSL-ADD	13.4	1.4	
41	Paks	1.40	PAK14	Loess	1,2,3,4,10	IRSL-ADD	15.2	1.5	
41	Paks	2.50	PAK15	Loess	1,2,3,4,10	IRSL-ADD	17.8	1.7	
41	Paks	3.23	PAK16	Loess	1,2,3,4,10	IRSL-ADD	15.5	1.5	
41	Paks	3.30	PAK2	Loess	1,2,3,4,10	IRSL-ADD	18.2	1.8	
41	Paks	5.10	PAK18	Loess	1,2,3,4,10	IRSL-ADD	18	1.6	
41	Paks	5.43	PAK3	Loess	1,2,3,4,10	IRSL-ADD	19.1	1.7	
41	Paks	5.90	PAK17	Loess	1,2,3,4,10	IRSL-ADD	19.2	1.7	
3	Remicourt	1.60	REM31	Loess	1,2,3,4,10	IRSL-ADD	18,7	1.8	
3	Remicourt	1.80	REM30	Loess	1,2,3,4,10	IRSL-ADD	20	1.9	
3	Remicourt	2.50	REM28	Loess	1,2,3,4,10	TL-ADD	25.8	2.8	
3	Remicourt	3.00	REM26	Loess	1,2,3,4,10	TL-ADD	23.8	3.1	
3	Remicourt	3.80	REM24	Loess	1,2,3,4,10	IRSL-ADD	24.4	5.6	
4	Rocourt	0.90		Loess	4,6,10	TL-REGEN	13.5	1.1	
4	Rocourt	1.50		Loess	4,6,10	TL-REGEN	13.2	1.1	
4	Rocourt	2.20		Loess	4,6,10	TL-REGEN	13.5	1.1	
4	Rocourt	2.50		Loess	4,6,10	TL-REGEN	17.1	1.4	Eltville tephra horizon
4	Rocourt	2.90		Loess	4,6,10	TL-REGEN	24.8	2.1	
6	Sables d'Or les Pins	1.00	SDP96-1	Sandy loess	1,2,3,4	IRSL-ADD	15.9	1.5	
6	Sables d'Or les Pins	1.30	SDP96-2	Sandy loess	1,2,3,4	IRSL-ADD	17.8	2.2	
6	Sables d'Or les Pins	1.60	SDP96-3	Sandy loess	1,2,3,4	IRSL-ADD	21.7	2.6	
6	Sables d'Or les Pins	1.90	SDP96-4	Sandy loess	1,2,3,4	IRSL-ADD	19.7	2	

6	Sables d'Or les Pins	2.20	SDP96-5	Sandy loess	1,2,3,4	IRSL-ADD	22.6	2.6	
6	Sables d'Or les Pins	2.50	SDP96-6	Sandy loess	1,2,3,4	IRSL-ADD	20.4	2.3	
6	Sables d'Or les Pins	2.80	SDP96-7	Reworked loess	1,2,3,4	IRSL-ADD	15.6	1.4	
6	Sables d'Or les Pins	3.10	SDP96-8	Reworked loess	1,2,3,4	IRSL-ADD			
6	Sables d'Or les Pins	3.20	SDP96-9	Reworked loess	1,2,3,4	IRSL-ADD	24.6	3.1	
6	Sables d'Or les Pins	3.40	SDP96-10	Reworked loess	1,2,3,4	IRSL-ADD	26.4	3.1	
7	Saint Sauflieu	0.80	SFL26	Reworked loess		Mean-LUM	15.1	1	
7	Saint Sauflieu	1.50	SFL25	Reworked loess		Mean-LUM	20.3	1.2	
7	Saint Sauflieu	2.00	SFL20	Reworked loess		Mean-LUM	21.9	0.2	
7	Saint Sauflieu	2.50	SFL19	Reworked loess		Mean-LUM	20.5	0.9	
7	Saint Sauflieu	2.90	SFL18	Reworked loess		Mean-LUM	20.3	0.1	
7	Saint Sauflieu	3.50	SFL17	Reworked loess		Mean-LUM	19.8	0.2	
7	Saint Sauflieu	4.00	SFL16	Reworked loess		Mean-LUM	20.2	1.2	
7	Saint Sauflieu	4.30	SFL15	Reworked loess		Mean-LUM	19.1	0.3	
7	Saint Sauflieu	4.50	SFL14	Reworked loess		Mean-LUM	18.8	0.4	
8	Saint-Romain	0.30	a	Loess	4,10	TL-REGEN	12.6	1.3	
8	Saint-Romain	0.60	b	Loess	4,10	TL-REGEN	14.4	1.3	
8	Saint-Romain	0.90	c	Loess	4,10	TL-REGEN	13.7	1.2	
8	Saint-Romain	1.20	d	Loess	4,10	TL-REGEN	14.2	1.3	
8	Saint-Romain	1.50	e	Loess	4,10	TL-REGEN	11.4	1	
8	Saint-Romain	1.70	f	Loess	4,10	TL-REGEN	16.4	1.5	
23	Schwalbenberg	0.40	SC44	Loess	1,2,3,4,5,10	IRSL-ADD	18.9	2.2	Frechen, unpublished
23	Schwalbenberg	0.70	SC43	Loess	1,2,3,4,5,10	IRSL-REGEN	16	3.5	Frechen, unpublished
23	Schwalbenberg	1.20	SC42	Loess	1,2,3,4,5,10	IRSL-ADD	17.2	2.8	Frechen, unpublished
23	Schwalbenberg	1.80	SC41	Loess	1,2,3,4,5,10	IRSL-ADD	17.4	4	Frechen, unpublished
23	Schwalbenberg	1.90	SC40	Loess	1,2,3,4,5,10	IRSL-ADD	18	2.1	Frechen, unpublished
23	Schwalbenberg	2.90	SC39	Loess	1,2,3,4,5,10	IRSL-REGEN	21.7	1.8	Frechen, unpublished
23	Schwalbenberg	3.00	SCHW3	Reworked loess	1,2,3,4,5,10	TL-REGEN	29.6	2.7	Zöller et al. (1991)
24	Schweinskopf	0.60	SK1	Loess	1,2,3,4,6,10	IRSL-ADD	14	2.8	
24	Schweinskopf	1.00	SK2	Loess	1,2,3,4,6,10	IRSL-ADD	13.1	3.2	
34	Stillfried	0.10	STILL 5d	Reworked loess	4,10,12	TL-REGEN	17.1	2.3	
34	Stillfried	0.20	STILL 5a	Reworked loess	4,10,12	TL-REGEN	16.5	2.3	
34	Stillfried	0.80	STILL 5b	Reworked loess	4,10,12	TL-REGEN	20.3	1.7	
34	Stillfried	1.10	STILL 5c	Reworked loess	4,10,12	TL-REGEN	25.4	3.7	
34	Stillfried	1.80	STILL B2	Reworked loess	4,10,12	TL-REGEN	27.5	3.6	
35	Stratzing	1.20	Stratz 3	Reworked loess	4,10,12	TL-REGEN	25.4	2.5	
25	Tönchesberg	0.40	T1	Loess	1,3,4,6,7,11,	TL-REGEN	14.8	1.8	
25	Tönchesberg	0.60	T2	Loess	1,3,4,6,7,11,	TL-REGEN	14.3	1.5	
25	Tönchesberg	0.75	T3	Loess	1,3,4,6,7,11,	TL-REGEN	15.7	1.8	
25	Tönchesberg	0.90	T4	Loess	1,3,4,6,7,11,	TL-REGEN			
25	Tönchesberg	1.10	T5	Loess	1,3,4,6,7,11,	TL-REGEN	14.1	1.5	
25	Tönchesberg	1.25	T6	Loess	1,3,4,6,7,11,	TL-REGEN	14.6	1.5	
25	Tönchesberg	1.40	T7	Loess	1,3,4,6,7,11,	TL-REGEN	15	1.6	
25	Tönchesberg	1.55	T8	Loess	1,3,4,6,7,11,	TL-REGEN	15.8	1.9	
25	Tönchesberg	1.70	T9	Loess	1,3,4,6,7,11,	TL-REGEN	16.4	1.7	
25	Tönchesberg	1.85	T10	Loess	1,3,4,6,7,11,	TL-REGEN	17.5	1.9	
36	Trindorf	0.50	Trin 1	Reworked loess	1,3,10	IRSL-ADD	16.7	1.8	
36	Trindorf	1.50	Trin 2	Reworked loess	1,3,10	IRSL-ADD	28.5	2.2	
36	Trindorf	2.40	Trin 3	Reworked loess	1,3,10	IRSL-ADD	29	2.8	
9	Villiers-Adam								

Table 2 (*continued*)

Location no.	Locality name	Depth below modern soil (m)	Lab-number	Material dated	Dating methods available	Method	Age (ka)	SD	Comments
26	Wallertheim	1.50	a	Loess	4,6,10	TL-REGEN	19.2	1.9	
26	Wallertheim	2.50	b	Loess	4,6,10	TL-REGEN	19	1.9	
26	Wallertheim	3.20	c	Loess	4,6,10	TL-REGEN	20.2	2	
26	Wallertheim	3.60	d	Loess	4,6,10	TL-REGEN	18.6	1.9	
27	Wannenköpfe	0.60	WAN10	Loess	1,2,3,4,6,10	IRSL-ADD	13.4	1.2	
27	Wannenköpfe	1.00	WAN9	Loess	1,2,3,4,6,10	IRSL-ADD	14	1.3	
27	Wannenköpfe	1.40	WAN8	Loess	1,2,3,4,6,10	IRSL-ADD	15	1.3	
27	Wannenköpfe	1.80	WAN7	Loess	1,2,3,4,6,10	IRSL-ADD	15.2	1.4	
27	Wannenköpfe	2.20	WAN6	Loess	1,2,3,4,6,10	IRSL-ADD	16.3	1.4	
37	Wels	1.00	Wels 1	Reworked loess	4,10,12	TL-REGEN	24	3	
37	Wels	1.50	Wels 2	Reworked loess	4,10,12	TL-REGEN	21	2	
38	Willendorf II	0.80	GrN-21898	Extern. bones 1	5,10	14C	23.86	0.27	
38	Willendorf II	0.80	GrN-22208	Extern. bones 2	5,10	14C	24.37	0.29	
38	Willendorf II	0.80	GrA-5006	Center of bone	5,10	AMS-14C	24.91	0.15	
38	Willendorf II	0.80	GrA-5005	Center of bone	5,10	AMS-14C	23.18	0.12	
38	Willendorf II	1.55	GrA-893	Charcoal	5,10	AMS-14C	23.2	0.14	
38	Willendorf II	1.55	GrA-493	Charcoal	5,10	AMS-14C	23.4	0.19	
38	Willendorf II	1.55	GrA-494	Charcoal	5,10	AMS-14C	23.67	0.12	
38	Willendorf II	1.95	GrA-917	Collagen extract	5,10	AMS-14C	22.18	0.19	
38	Willendorf II	1.95	GrA-894	Charcoal	5,10	AMS-14C	24.71	0.18	
38	Willendorf II	1.95	GrN-17801	Charcoal	5,10	14C	25.23	0.32	
38	Willendorf II	1.95	GrN-17802	Charcoal	5,10	14C	25.66	0.35	
38	Willendorf II	1.95	GrN-21690	Bone	5,10	14C	25.4	0.17	
38	Willendorf II	1.95	GrN-20767	Bone	5,10	14C	25.44	0.17	
38	Willendorf II	2.10	GrA-491	Charcoal	5,10	AMS-14C	23.83	0.2	
38	Willendorf II	2.10	Gr-492	Charcoal	5,10	AMS-14C	23.99	0.13	
38	Willendorf II	2.35	GrN-20768	Charcoal	5,10	14C	26.5	0.48	
38	Willendorf II	2.35	GrA-1016	Charcoal	5,10	AMS-14C	26.15	0.48	
38	Willendorf II	2.35	GrN-17803	Charcoal	5,10	14C	27.6	0.48	
38	Willendorf II	2.35	GrA-895	Charcoal	5,10	AMS-14C	27.62	0.23	
30	Zemechy	1.50	ZE 16	Loess		IRSL-ADD	15.7	1.8	
30	Zemechy	2.50	ZE 17	Loess		IRSL-ADD	17.8	1.9	
30	Zemechy	4.00	ZE 15	Loess		IRSL-ADD	19.6	2.1	

Dating methods available include:
(1) Infrared optically stimulated luminescence, additive dose method (IRSL-ADD).
(2) Infrared optically stimulated luminescence, regeneration method (IRSL-REGEN).
(3) Thermoluminescence, additive dose method, total bleach (TL-ADD).
(4) Thermoluminescence, regeneration method (TL-REGEN).
(5) Radiocarbon including conventional and ^{14}C AMS.
(6) Tephrochronology.
(7) Palaeomagnetism.
(8) TIMS U/Th.
(9) Varve chronology.
(10) Loess stratigraphy.
(11) $^{40}Ar/^{39}Ar$ laser fusion single grain dating.

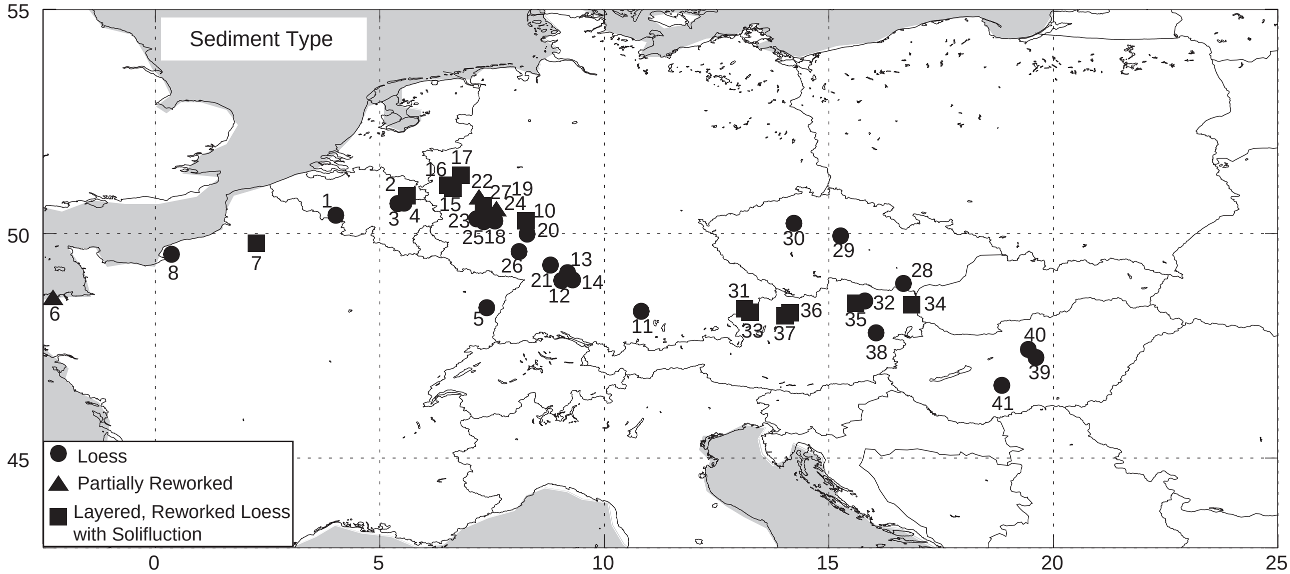

Fig. 3. Locations and dominant facies types of OIS 2 loess considered here.

Although other relative dating methods such as amino acid racemization (AAR) of loess snails (Oches and McCoy, 1995) and tephrochronology (Frechen, 1992; Bogaard, 1995) are used for age control in work on European loess deposits, they have not been employed in this study.

In northwest and central Europe, an erosion event occurred at about 18–17 ka BP, as indicated by a hiatus in many loess sections in the Middle Rhine area (Frechen, 1992), in the Beuningen gravel bed in Belgium (Frechen et al., 2001b) and in the Netherlands (Frechen and van den Berg, 2002). Thus, two different mass accumulation rates have been calculated for the Last Glacial Period, i.e. deposition between 28 and 18 ka BP and between 18 and 13 ka BP. Within these periods, MARs were calculated for each section of those intervals in which deposition appears to have been continuous. Kohfeld and Harrison (2003) provide background information on the MAR calculation, including the relevant equations and parameters used. In this paper, a constant bulk density of 1.65 g/cm^3 is used for loess (Pye, 1987) in converting sedimentation rates to mass accumulation rates. Luminescence ages with standard deviations greater than 15% were rejected. Estimating MARs at certain sections was often complicated because of evidence of extremely rapid deposition and the presence of small discontinuities that resulted in age estimates at different depths that are analytically indistinguishable. In these instances minimum and maximum MARs were estimated for these zones. Fig. 3 shows the location of all sites in Europe investigated in this study and the main sediment type related to the units under investigation. The purpose here is to examine the MARs of primary loess, i.e. material assumed to be aeolian in origin. Although MARs have been calculated for all loess sections that have a sufficient number of available dates, MARs determined for reworked loess are not included in the figures or the discussion.

7. Mass accumulation rates during the Last Glacial Period (OIS 2)

Mass accumulation rates for primary loess deposits laid down in the Pleniglacial period (28–18 ka BP) range from 100 to 7000 g/m^2/yr (Figs. 4, 6). Highest accumulation rates are associated with the sites in western Germany along the Rhine River system, e.g. Wallertheim (site 26) (terrace, 6930 g/m^2/yr) and Nussloch (site 21) (plateau, 1213–6129 g/m^2/yr). Lowest accumulation rates (93–450 g/m^2/yr) are found at sites in Belgium at Kesselt (site 2), Remicourt (site 3) and Rocourt (site 4) and in eastern France at Achenheim (site 5), represented by three slope sites and one terrace location.

The Lateglacial (i.e. 18–13 ka BP) mass accumulation rates are between about 200 and 450 g/m^2/yr in France, including sections near the coast and along rivers such as the Somme and Seine (Figs. 5, 6). Along the Rhine and its tributaries, MARs are significantly higher. Most of the loess sites on terraces have a MAR between 800 and 1600 g/m^2/yr, with a few sequences reaching values of 1600–3200 g/m^2/yr. Highest accumulation rates are found in Lower Austria (Grubgraben, site 32), Moravia (Dolni Vestonice, site 28) and Hungary (Paks, site 41) with MARs between 1600 and 3200 g/m^2/yr along the Danube (Figs. 4–6).

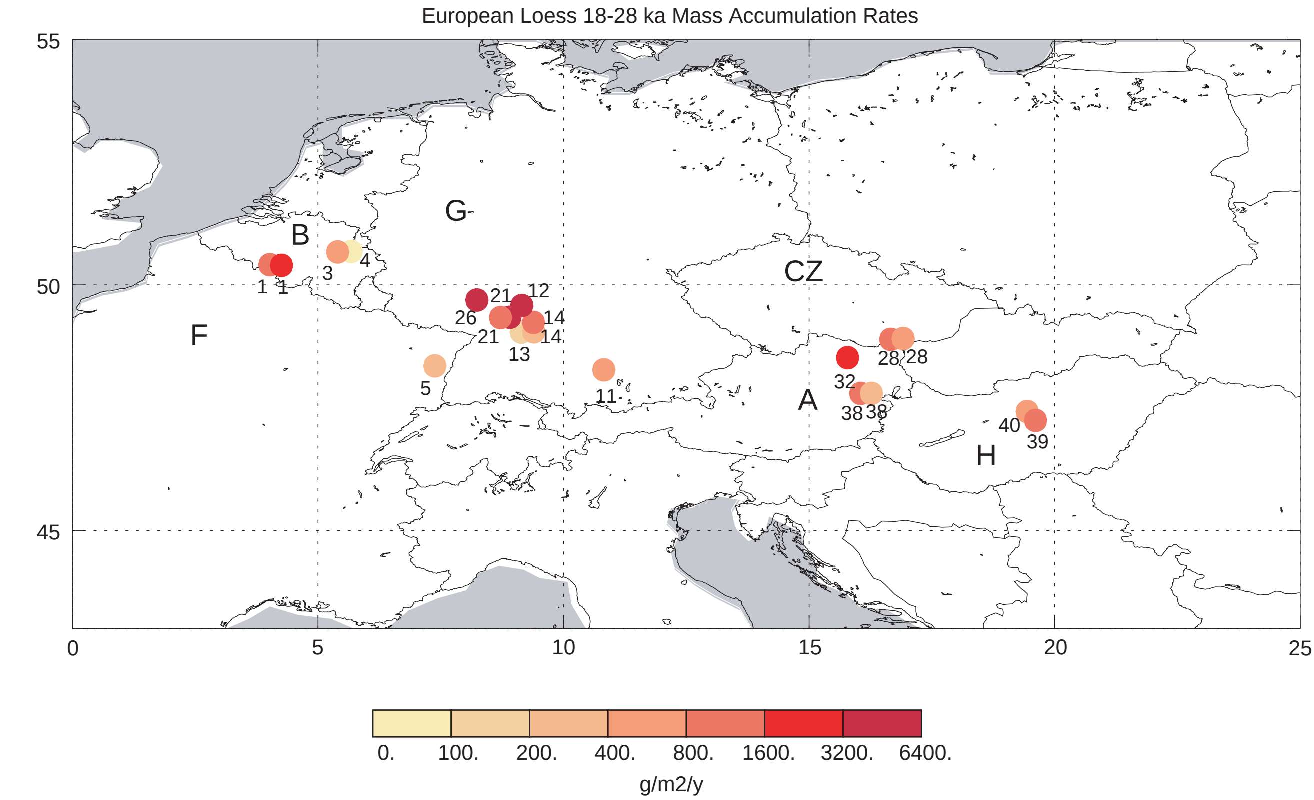

Fig. 4. Mass accumulation rates for European loess sites during the Pleniglacial period (28–18 ka BP).

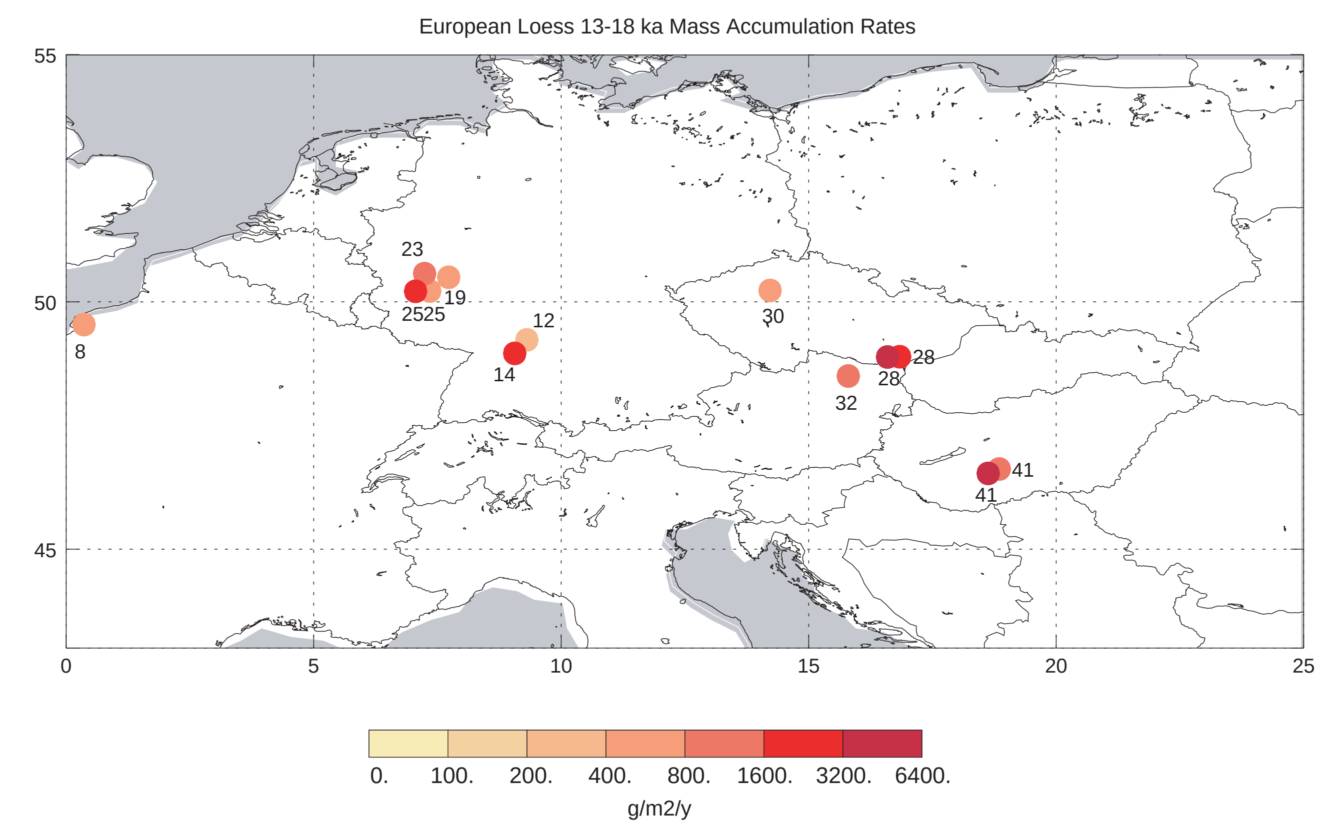

Fig. 5. Mass accumulation rates for European loess sites for Lateglacial time (18–13 ka BP).

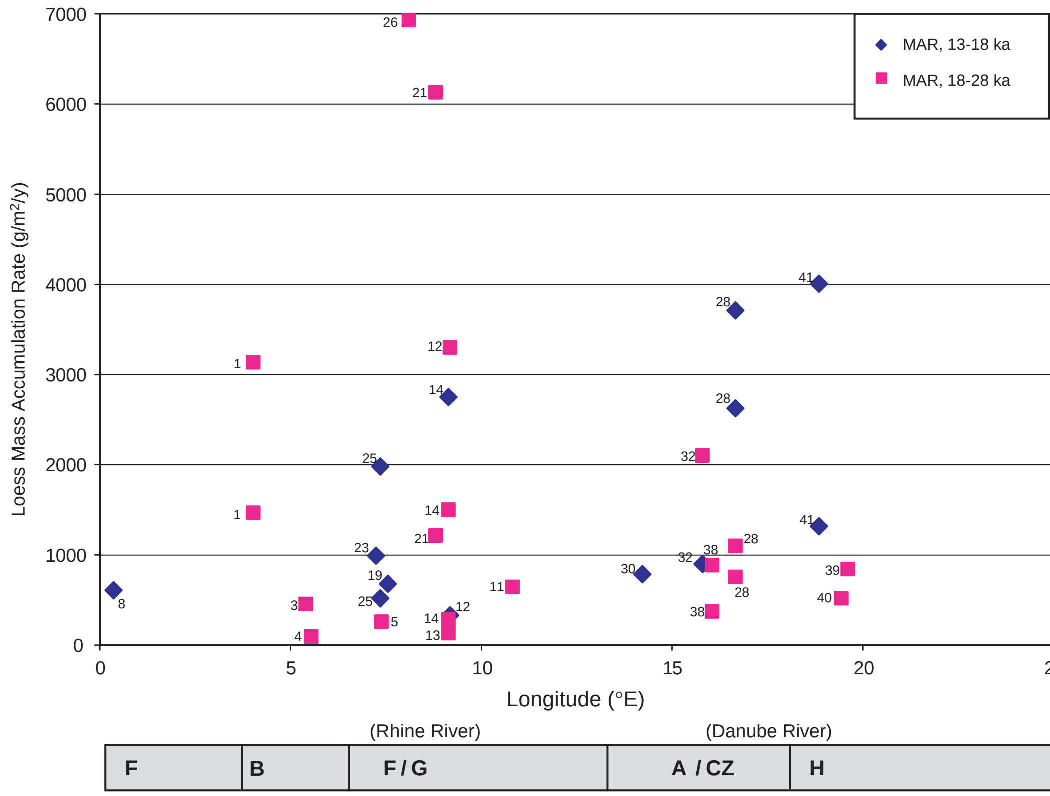

Fig. 6. Mass accumulation rates for OIS 2 (in g/m^2/yr) versus longitude.

Today, a climatic gradient exists between the maritime Atlantic coast in the west and the more continental climatic conditions on the Russian Plain in the east. Although a slight northwest-to-southeast increase in accumulation rates is apparent for the Lateglacial period (Fig. 6), recognizing this climatic trend in the mass accumulation rates along the European transect is complicated by the local influence of large river systems, notably those of the Rhine and the Danube. Along the Rhine system alone, accumulation rates vary by an order of magnitude, with terrace sites having much higher MARs than non-terrace locations. Furthermore, the deposits along the Rhine are composed predominantly of silt with a mixture of sand grains, which strengthens the case for a primarily local source of material.

One possible explanation for these extremely high accumulation rates is the probable enhancement of fluvio-aeolian recycling of silt-rich material during glacial periods. The transport of glacially derived fine-grained debris from mountain sources such as the Alps to regions of deposition along the floodplains is supported not only by the known distribution of Quaternary facies but also by the clear decline in loess thickness with distance from the river system, as reported for the Middle and Lower Rhine (Meyer, 1989; Henze, 1998).

8. Summary and conclusions

Many European loess sequences contain much of the record of the last interglacial–glacial cycle, thus spanning the past ~130 ka. Above the last interglacial palaeosol, many European loess sections contain detailed records of climate changes during the last (Weichselian) glacial period, which spans OIS 2, 3, and 4 and perhaps the later sub-stages of OIS 5. During the period of time since the last interglacial period (OI sub-stage 5e), intervals of dust accumulation are represented by relatively unaltered loess. Although unconformities are present in these loess sections, sufficient numbers of luminescence ages exist to allow calculation of MARs for the Last Glacial Period (OIS 2).

This paper is a first attempt to quantify the mass accumulation rates of loess at key sites in continental Europe, in order to place them within the context of the global dust cycle. The MAR calculations presented here show a range of accumulation rates from ~100 to 7000 g/m^2/yr, with the lowest rates of accumulation being found at sites in France and Belgium in the northwest part of the transect. Higher accumulation rates occur towards the southeast (Czech Republic, Austria, Hungary).

On general grounds, loess mass accumulation rates might be expected to reflect the regional climatic gradients across Europe, with more maritime conditions near the Atlantic coast resulting in lower dust accumulation rates, and the more continental environments to the southeast producing higher rates. However, the highest dust accumulation rates are found at terrace sites along the major river systems such as the Rhine. Thus, patterns of dust accumulation appear to be dominated by changes in local sources, adding complexity to the process of regional correlation of loess accumulation rates and regional climatic gradients across the continent.

Mass accumulation rates for the Last Glacial Period (OIS 2) in Europe are relatively high, when considered globally. Although the lowest MARs are found in the northwest part of the transect (e.g. $\sim$100–600 g/m^2/yr), those along the Rhine and extending into Eastern Europe are consistently high, ranging from 800–3200 g/m^2/yr. On average, these rates are higher than those in China (Kohfeld and Harrison, 2003) and Alaska (Muhs et al., 2003), being more closely comparable to some MARs calculated for central North America (Bettis et al., 2003). European loess MARs during the Last Glacial Period (OIS 2) are higher than almost all aeolian MARs calculated for the world's oceans (Kohfeld and Harrison, 2000, 2001).

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