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Late Pleistocene Climatic Variations at Achenheim, France, Based on a Magnetic Susceptibility and TL Chronology of Loess

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New field investigations of the Achenheim sequence (Alsace, France) allow for the characterization of variations in the low-field magnetic susceptibility over most of the last climatic cycle, i.e., the past 130,000 yr. New stratigraphic data and thermoluminescence measurements permit reassessment of the previous chronological interpretation of the Upper Pleistocene at Achenheim. A high-resolution analysis of magnetic susceptibility discloses the occurrence of a fine-grained "marker" horizon which was also found recently in another section. This horizon is interpreted as a small-scale dust layer deposited prior to the main interval of loess deposition. The horizon, deposited at the marine isotope stage (MIS) 5/4 boundary, has been found in other loess sequences and is especially prevalent in central Europe. It is characterized by low susceptibility values and a grayish color. New thermoluminescence dates indicate that the loess deposition took place after the MIS 5/4 boundary, i.e., after 70,000 yr. These results are consistent with the Greenland GRIP ice-core dust record which also demonstrates a dusty atmosphere after 72,000 yr ago. On a more regional scale, the Achenheim loess sequence demonstrates a reliable correlation between the western side of the Eurasian loess belt and the dust record of the Greenland ice cores.

Key Words: **magnetic susceptibility; loess; last climatic cycle; Greenland; dust; thermoluminescence; Alsace; France.**

INTRODUCTION

European loess–soil sequences have been investigated for a long time and provide a complete record of the European continental Quaternary. Correlation of these records with those from Alpine glaciers, peat bogs, and marine isotopes have been proposed (Kukla, 1977). Although studied from a stratigraphic point of view, some indicators, among them fossil snail assemblages, are good indices of the climatic changes recorded (Kukla and Lozek, 1961). In the Achenheim sequence (Alsace, France, 48°35′N, 7°38′E), analysis of the mollusk content has allowed the characterization of five superimposed climatic cycles (Puisségur, 1978; Rousseau, 1987; Rousseau and Puisségur, 1990). Temperature and precipitation estimates, obtained using transfer functions from the snail assemblages, were reconstructed for the last three glacial–interglacial cycles (Rousseau, 1991). Although no physical parameters were studied, correlations with the marine isotope stages (MIS) were proposed based on geomorphology, sedimentology, ^{14}C and TL (thermoluminescence) dates, and the analysis of mollusk assemblages (Rousseau and Puisségur, 1990). In the present study, we made new TL measurements and investigated the low-field magnetic susceptibility (MS) of the Upper Pleistocene section at Achenheim (Fig. 1). We were then able to determine more precisely the stratigraphy of the lower units of the last climatic sequence and to propose correlations with the Greenland ice-core record (GRIP, 1993).

The MS permits characterization of climatic changes in eolian deposits (Heller and Liu, 1984; Kukla, 1987). Correlations have been proposed between magnetic records from Chinese loess and magnetic records, dust content, and isotope variations in marine cores (Kukla *et al.*, 1988; Hovan and Rea, 1991) and with the dust content of ice cores (Petit

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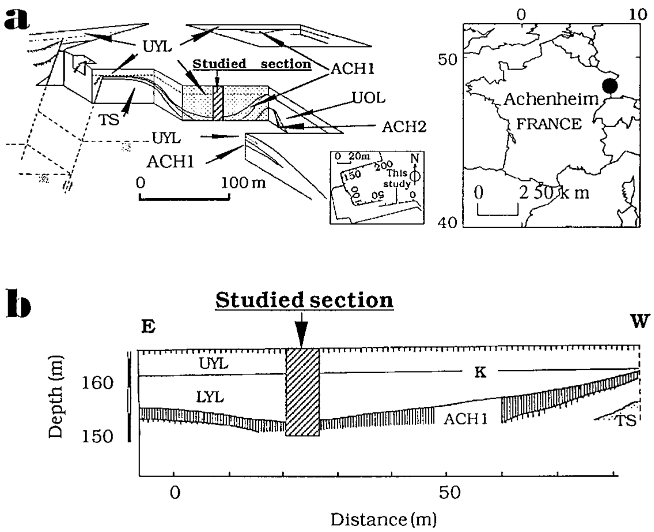

FIG. 1. Map and diagrams showing the location and stratigraphy of the Achenheim loess deposits in the Hurst brickyard (modified from Heim *et al.*, 1982). (a) Location of the Hurst outcrops resulting from the exploitation of the quarry. The main section (gray pattern) covers the last climatic cycle, previously studied by Sommé *et al.* (1986) and Rousseau *et al.* (1994). (b) Stratigraphic profile of the southern wall of the Hurst brickyard in Achenheim. UYL, Upper Younger Loess; K, Nagelbeek mark line; LYL, Lower Younger Loess; ACH1, Achenheim I pedocomplex. Penultimate climatic cycle: UOL, Upper Older Loess; ACH2, Achenheim II pedocomplex; TS, terrace sediments interpreted as corresponding to MIS 12–13 (Rousseau, 1987).

et al., 1990). Whereas several hypotheses exist concerning the origin of the magnetic grains in the soils (Kukla, 1987; Maher and Taylor, 1988; Maher and Thompson, 1991; Verosub *et al.*, 1993; Zhou *et al.*, 1990), the MS in soils is generally higher than in loess, especially in Europe, China, and North America (Kukla and An, 1989; Kukla *et al.*, 1990; An *et al.*, 1991; Rousseau and Kukla, 1994).

STRATIGRAPHY AND METHODS

Stratigraphy

The stratigraphy of the Upper Pleistocene sediments at Achenheim consists of two major units (Sommé *et al.*, 1986) (Fig. 2). At the bottom lies the so-called ‘‘Grand Lehm,’’ or Achenheim I pedocomplex, which includes an interglacial horizon characterized by clayey, dense, brown loam with sparse ferromanganese nodules (2–4 mm) interpreted as a Bt horizon of leached brown soil having prismatic structures. This soil complex is overlain by a black soil (10 YR 3/3) and brown loams (10 YR 8/4) with some interbedded grayish units (Sommé *et al.*, 1986) (Fig. 2). The lower part of this unit was investigated by digging a 3-m-deep trench. The basal unit was stated to be 6.55 m thick (Sommé *et al.*, 1986).

Overlying the Achenheim I pedocomplex is a loess unit, the Younger Loess, which is 12.35 m thick. At the bottom of the loess is a yellowish sediment that becomes grayish from 12.35 to 5.20 m depth. A level with large frost wedges (at 5.20 m) marks a transition to gray loess with brown bedded layers near its top. This loess (5.20 to 2.80 m) ends with a horizon that is recognized throughout a wide area of western Europe (Sommé *et al.*, 1986). This reference level is characterized by slightly organic tongues of soil and is seen in northwestern European sequences in the upper part of the Weichselian calcareous loess. In Belgium this marker has been formally named the Nagelbeek Horizon (Haesaerts *et al.*, 1981). It was first dated to about 21,000–22,000 ^{14}C yr B.P. (Haesaerts *et al.*, 1981) but now is interpreted as lying at the marine isotope stage (MIS) 3/2 boundary (Juvigné *et al.*, 1996). The subunit bracketed by the pedocomplex and the Nagelbeek level corresponds to the Lower Younger Loess (‘‘Loess récent inférieur’’) (Schumacher, 1912; Wernert, 1957) (Fig. 2). Finally the Younger Recent Loess subunit corresponds to a gray loess (2.8 to 0.3 m) and lies below the present soil (0.30 m) on top of the sequence (Sommé *et al.*, 1986) (Fig. 2).

Previous studies interpreted the pedocomplex as correlative with MIS 5 based on sedimentology, micromorphology, and mollusks. The interglacial Bt horizon was interpreted as corresponding to substage 5e (Sommé, 1990). The loess

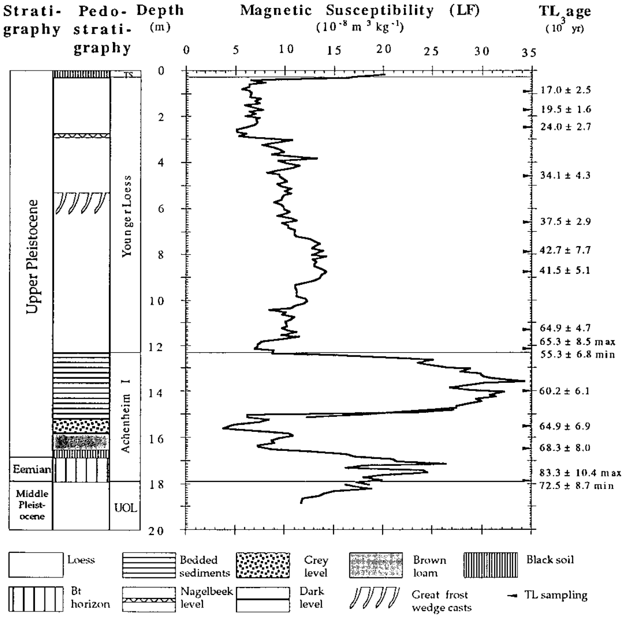

FIG. 2. Upper Pleistocene section representing the last climatic cycle at Achenheim. On the left, stratigraphic interpretation of the sequence after Rousseau and Puisségur (1990) and Sommé *et al.* (1986). On the right, variation of magnetic susceptibility with depth and location of thermoluminescence (TL) samples and their ages.

deposits were then assigned to MIS 2 and 3 based on ^{14}C and TL (thermoluminescence) dates and mollusk studies (Rousseau and Puisségur, 1990).

Magnetic Susceptibility

After carefully cleaning the section, sediment was sampled at 10-cm intervals and then measured in the laboratory at low and high frequency with a MS2 Bartington MS2 magnetometer and MS2B sensor. Some direct readings were made on the outcrop in order to check the laboratory measurements.

The characterization of the main mineralogical families (hematite and magnetite) can be established through the S ratio resulting from a study of the isothermal remanent magnetization (IRM). This ratio is expressed as $S = -[\mathrm{IRM}\,(-0.3 \times T)/\mathrm{IRM}\,(1T)]$. IRM $(-0.3 \times T)$ is the magnetization gained in a field of 0.3 Teslas, and IRM $(1T)$ is the magnetization in a field of 1 Tesla. Low values of the S ratio allows characterization of antiferromagnetic minerals like hematite.

TL Dating

The Achenheim chronology is mainly based on TL dates. Dating sediments by TL is based on the physical phenomenon that visible and UV light is able to reduce (bleach) the latent TL signal to a small residual value if the illumination is long enough (‘‘total bleach’’). For loess grains, a few hours or days of sunlight or daylight exposure is sufficient, whereas a shorter illumination results in a ‘‘partial bleach’’ which can lead to TL age overestimates if total bleach laboratory techniques are applied. The danger of overbleaching can be minimized by using optical (OSL) or infrared-stimulated luminescence (IRSL). As these methods have not yet been tested for older loess as extensively as has TL, for all samples mentioned in this study the approved techniques of TL dating developed in the Heidelberg laboratory were applied and supplemented by partial bleach experiments (see below). Furthermore, one sample from the youngest loess from Achenheim was also measured using IRSL in order to test the reliability of the partial bleach experiments.

A TL age is calculated as the ratio ED/DR with ED being the equivalent β or γ radiation dose of the sample received since the event to be dated and DR being the effective dose rate of natural radiation. The dating procedure requires both an estimation of the absorbed dose since deposition of the sediment and the evaluation of the natural radioactivity (Aitken, 1985; Zöller, 1995; Zöller *et al.*, 1994). Many steps are necessary in order to verify a TL age according to different methods for ED estimation and radioactivity analysis. It has always been the philosophy of the Heidelberg luminescence laboratory to handle each sample carefully, rather than running an excessive number of samples in a routine manner, as luminescence dating of sediments cannot yet be regarded as a routine method.

Samples for TL dating were collected in light-proof steel cylinders and processed under well-defined subdued red laboratory light. For TL measurements, the 4- to 11-μm polymineralic fine-grained fraction was extracted by wet sieving and settling in 0.01 N NH_3OH (Stokes' law). Following decalcification in 10% HCl and removal of organic matter in 30% H_2O_2, the 4- to 11-μm fraction is placed on aluminum discs in acetone. A portion of the aliquots is bleached for 3 h under a Dr. Hoenle SOL2 solar simulator lamp (6.5-fold the natural sunlight intensity in July at northern hemisphere mid-latitudes). Calibrated ^{90}Sr (ca 10.5 Gy/min) and ^{241}Am sources (0.337 mm^{-2} min^{-1} alpha track length) were used for laboratory irradiation. After ionizing irradiation, the aliquots were stored at 70°C for 1 week to allow anomalous fading of the TL signal to settle. TL measurements were executed at a ramp rate of 5 K s^{-1} to 500°C. TL signals were recorded in a Littlemore ELSEC 7185 reader with a quartz-windowed EMI9635Q photomuliplier and a narrow blue-transmittant Corning 5-58 and a Chance-Pilkington HA-3 filter glass in front of it. This filter combination transmits luminescence emissions with better long-term stability than shorter or longer wavelength emissions (Krbetschek *et al.*, 1996). During TL readout, thermally unstable TL signals were removed by holding the temperature at 270°C for 60 s (older samples) or 240°C for 20 s (younger samples).

The latter preheat technique has been tested for a range of last-glacial loess samples and was found to remove unstable signals sufficiently from the partially stable 240°C glow peak. The ED plateau test (additive dose technique) needs to be performed, as was recently emphasized again by Berger (1994). The advantage over the 270°C preheat technique is that a great portion of the more light-sensitive 270–280°C glow peak is retained and can also be processed for age estimation.

Most Lower Weichselian sediments contain reworked loess units or soil parent material, which may or may not have been well-bleached at deposition. Consequently, total bleach laboratory techniques can easily overestimate the TL ages. This is particularly true if wide areas under the glow curves are integrated for the estimation of ED, rather than using an ED plateau obtained from 5 or 10°C intervals of the glow curves. However, long ED plateau, i.e., a long glow curve temperature range yielding identical ED estimates, can serve as a check for the state of bleaching at deposition. Assuming that beyond a certain glow temperature, e.g., 300°C, the thermal stability of the TL signal is sufficient for dating beyond 100,000 yr, the different sensitivity of TL glow peaks to daylight is supposed to indicate reliably whether or not the bleaching procedure in the laboratory closely matched the natural conditions at deposition. If an easy-to-bleach glow peak yields the same TL age as a hard-to-bleach glow peak, one may infer that the laboratory bleaching was appropriate. However, if the hard-to-bleach glow peak suggests an older TL age than an easy-to-bleach glow peak, overbleaching in the laboratory is most likely. Correspondingly, underbleaching is expected if the hard-to-bleach glow peak yields a younger TL age than the easy-to-bleach glow peak. The ''longest ED plateau'' technique (Mejdahl, 1985) determines the state of bleaching when performing partial bleaching experiments with various illumination periods and/or conditions, i.e., full sunlight, shaded sunlight, diffuse daylight can be shown empirically, the natural TL glow curves of fine loess grains measured using these experimental conditions consist of overlapping glow peaks with different sensitivities to light. The longest plateau technique is expected to be valid for the estimation of ED. The application of this technique to fine polymineralic loess grains is relatively untested (Proszynska-Bordas *et al.*, 1988). Therefore, for all samples dated using the longest plateau technique, the apparent TL ages calculated from the short plateau obtained by the total bleach technique will also be mentioned as maximum ages.

Radioactivity analysis was performed using independent methods and approaches. The first approach is to measure α, β, and γ dose rates separately using α and β counting and on-site γ scintillation counting or multichannel spectrometry, respectively. The second approach is to estimate concentrations of ^{238}U, ^{232}Th, their relevant daughter isotopes, and ^{40}K by high-resolution γ spectrometry using Ge detectors and calculate their dose rates using the conversion factors given by Nambi and Aitken (1986). The advantage of this procedure is that it allows detection of significant secular disequilibrium in the ^{238}U decay chain. The first procedure, however, typically results in smaller random errors if an equilibrium state has been proved by high-resolution γ spectrometry or, in case of disequilibrium, if it is evident that the disequilibrium has persisted over the entire time span to be dated. In the calculation of the effective natural dose rate, allowance is made for the α-value (α efficiency factor), the representative interstitial water content of the sample, and the small amount of cosmic dose rate. Past changes of moisture are estimated, typically as ±25% of the present moisture content measured far enough behind the dry exposure surface. All errors quoted are 1σ errors.

RESULTS

Our investigation recognized the main units previously determined in the sequence. However, the observed detailed stratigraphy indicates a new horizon, not previously described, at the bottom of the sequence (Fig. 2).

The pedocomplex Achenheim I can be divided into two main subunits. The lower part starts at the top of the Upper Older Loess that is overlain by a Bt horizon and ends at a level of calcareous granules. It comprises, respectively, the so-called interglacial paleosol, a black steppe soil (0.25 m), a brown loam (0.8 m), a gray loam (0.5 m), and calcareous granules. Although the basal limit of the brown loam is clearly defined, its top is underlain by a bedded layer, including a thin (1 cm) dark band. This dark unit is overlain by a reddish-orange one, above which a fine-grained gray loam shows traces of hydromorphy. The 0.5-m-thick gray loam was not known prior to this study. The fine-grained sediment indicates completely different environmental conditions than during previous intervals of sedimentation. The upper part of pedocomplex (3.2 m) includes brown loams in which several thin white bedded layers occur together with charcoal. Achenheim I is thus 5.9 m thick.

The loess unit (Younger Loess) can be divided into three main subunits, the boundaries of which are well defined. The lower subunit starts at the top of the pedocomplex and ends at the level of large thin frost wedge casts. This first subunit comprises, respectively, yellowish, grayish, and more-compact brownish loess layers. The middle subunit begins at the wedges and ends with the Nagelbeek level. This second element comprises a gray loess, a bedded (grayish mm-thick layers) loam with small frost wedge casts, and an yellowish-brown loess. The upper subunit begins at the Nagelbeek level and ends at the modern topsoil. The Upper Younger Loess is marked by color variations ranging from greenish-gray to yellowish-gray and encompasses several layers of small concretions.

The low field frequency (LF) MS values range between 3 and 35×10^{-8} m^3 kg^{-1} (Fig. 2). The highest values are from the Bt horizon, the upper subunit of pedocomplex Achenheim I, and the top soil. The Achenheim I pedocomplex shows a threefold variation of MS. At the base, MS increases from 10 to 25×10^{-8} m^3 kg^{-1} to the top of the Bt horizon. Then MS decreases regularly in the black soil to reach 7×10^{-8} m^3 kg^{-1} in the mid-brown loam. MS increases again through the loam but shows a new but strong decrease to the lowest values of the total sequence in the middle part of the gray fine-grained unit. The values increase again to reach 35×10^{-8} m^3 kg^{-1} in the middle of the bedded unit which ends the Achenheim pedocomplex. MS then decreases up to the top of Achenheim I. The average value of MS in the Achenheim I is 19.11 ± 8.59, while the mean value in the loess is 9.86 ± 2.33 10^{-8} m^3 kg^{-1}.

The transition between the Achenheim I pedocomplex and the loess is sharp and well displayed in the MS values. Within the Younger loess, the susceptibility values range between 5 and 15. The lowest values occur at the lower boundary and above the Nagelbeek horizon. Similar low levels were obtained in other European Upper Pleistocene loess sequences in Normandy, west of Achenheim (Antoine *et al.* in press), and at Nussloch, in the Rhine valley, north of Achenheim (D. D. Rousseau, unpublished data).

A preliminary study of the rock magnetic properties in the Achenheim sequence was made on loess samples from the Upper Younger Loess (UYL) subunit and from the bottom of the Achenheim I (ACH1) pedocomplex (Le Meur, 1994). The S ratio varies between 0.85 and 0.88 in the loess samples and between 0.88 and 0.94 in the soils and paleosol. It can be inferred from these values that the loess units are richer in hematite than the soils and paleosol. Maher and Thompson (1991) obtained comparable values in the Chinese loess sequence ($0.7 < S < 0.8$ in soils and $0.54 < S < 0.75$ in loess). Although the total concentration in magnetic minerals is higher in the loess units, there are many more fine grains of magnetite in the soils, which supports a pedogenic origin of these grains (Maher and Thompson, 1991; Zhou *et al.*, 1990). The granulometry of the magnetite is coarser in the soils than in the loess samples measured. The susceptibilities of the Younger Loess are generally higher than those defined in Karamaidan (Tajikistan) or Xifeng (China) (Forster and Heller, 1994), whereas the variations through time are similar in both regions.

INTERPRETATION

The stratigraphic sequence of the pedocomplex Achenheim I includes a new horizon, a gray layer, not previously described in studies of the main section. This new stratigraphy of Achenheim I is similar to the sequence described in another section recently by Rousseau *et al.* (in press). There, a fine-grained unit has been recognized overlying a Bt horizon and a black steppe soil sequence (Rousseau *et al.*, in press). This horizon, interpreted as an abrupt dust event, is overlain by pellet sands that represent the removal of black soil and Bt sediment. A TL date indicates that this abrupt dust event corresponds to ‘‘Marker II,’’ described by Kukla and Lozek (1961), which occurs at the MIS 4/5 transition (Kukla, 1977) in the European loess stratigraphy (Rousseau *et al.*, in press). In the present study, the gray fine-grained subunit, based on the TL date of 64,900 ± 6900 yr, is interpreted as equivalent to Marker II.

A previous TL date (51,000 ± 10,600 yr) obtained at the very base of the Younger Loess (Aitken *et al.*, 1986) supports such an interpretation. Consequently, the sequence including the interval from the gray level to the top soil is interpreted as being equivalent to marine isotope stages 4, 3, and 2. Previous interpretations (Sommé *et al.*, 1986; Rousseau and Puisségur, 1990) considered the MIS 4 part of the record to be missing. New TL investigations of the Upper Pleistocene in Achenheim support this interpretation (Zöller *et al.*, in press). The base of the Younger Loess has a maximum age of 65,300 ± 8500 yr (total bleach technique), and a minimum age of 55,300 ± 6800 yr (longest plateau technique). The gray level is dated 64,900 ± 6900 yr, an age that is in agreement with its stratigraphic position within the European framework determined by Kukla (1977).

Even more surprising is the fact that the Bt horizon at the base of the sequence has two different ages (83,300 ± 10,400 yr maximum and 72,500 ± 8700 yr minimum) which are different from the Eemian interglaciation (*sensu stricto*), as previously interpreted. The TL age of the Bt horizon may be underestimated due to increasing dose rate since deposition, a problem previously encountered in soils (Zöller and Wagner, 1990). It can lead to significant TL age underestimates if the enrichment of radionucleids in soils (mainly due to decalcification and K accumulation by small roots) happened fairly recently, i.e., long after sedimentation. Increasing dose rate can also arise due to precipitation of radionucleids from groundwater. For the Bt sample, no significant secular disequilibrium was detected, but it cannot be precluded for any period since burial. Assuming that the high natural radioactivity of the paleosol (effective dose rate is 4.62 mGy/a) is a very recent artifact, which is very unlikely based on palaeopedological considerations, and during most of the burial time the natural dose rate was similar to the older loess of MIS 6 age (e.g., 3.22 mGy/a for a sample beneath the paleosol dated 139,000 ± 11,000 yr B.P. and 3.83 mGy/a for another dated 133,000 ± 13,000 yr B.P.), the ED of the Bt sample should be a minimum value that is nearly the same as that for older loess samples. This is not the case, however, as the ED of the Bt horizon is only 335 Gy (longest plateau) to 380 Gy (TB) compared to 447 and 510 Gy for older loess samples. This fact supports the interpretation that the Bt horizon formed much later than the MIS 6 loess. This can have contributed to underestimation of the parent TL age.

A TL date of 17,000 ± 2500 yr was obtained 0.6 m below the topsoil. Another TL date sample from 2.4 m depth, 0.4 m above the Nagelbeek level, has an age of 24,000 ± 2700 yr. These two dates indicate that the loess sequence does not end 12,000 yr ago, as previously interpreted. The dates from the top of the sequence indicate that loess deposition ceased about 16,000 yr ago. Moreover, the Nagelbeek level must be older than inferred in previous studies, which followed the interpretation of Juvigné and Wintle (1988) who adopted an age of 16,000 yr for it. The new interpretation places the so-called Nagelbeek level at the MIS 3/2 boundary in the SPECMAP chronology (Martinson *et al.*, 1987), as previously postulated for northern France and Normandy.

This interpretation of the Upper Pleistocene sequence is radically different from the previous one based mainly on stratigraphic correlation. The Achenheim I pedocomplex was interpreted as equivalent to MIS 5, MIS 4 was lacking, and MIS 2 was thicker. According to the new interpretation, almost 16 m of the sequence dates from MIS 4 to the main part of stage 2. The excess representation of MIS 4 is due to the bedded sediments above the Marker II. The new TL dates for the Upper Pleistocene sequence in Achenheim show that loess sedimentation corresponds to the interval 55,300 to 15,000 yr ago.

DISCUSSION

The fine-grained loess of the Achenheim sequence was deposited during isotope stages 4, 3, and 2, which are the dustiest stages of the Late Pleistocene. The chronology proposed for the Younger Loess implies a possible correlation of the European loess sequence with the ice-core dust record of Greenland. A correlation has been proposed between the Chinese loess sequence and the GRIP ice-core (Porter and An, 1995). By contrast, the Achenheim sequence is located in western Europe, where the climate was directly influenced by the same North Atlantic variations as detected in the GRIP ice-core record (Dansgaard *et al.,* 1993). Except for a dust event during the Younger Dryas interval, ice-core dust sedimentation ended ca. 14,500 yr ago. This implies that the top of the Late Pleistocene section in Achenheim lacks the Younger Dryas event, with the base of the topsoil dating to ca. 15,000 yr. The bottom of the loess deposit has a minimum age of 55,300 ± 6800 yr and a maximum age of 65,300 ± 8500 yr and lies above Marker II at the 5/4 boundary dated 73,900 yr (Martinson *et al.,* 1987). According to this chronology, the 5/4 Marker corresponds to the dust event dating 73,000 yr in the GRIP record. This dust peak precedes a major dust event 68,000–70,000 yr ago which marks the beginning of the dustiest interval of the Late Pleistocene at the GRIP site. These dates agree with the maximum TL dates of 65,300 ± 8500 yr at Achenheim.

Assuming that the TL dates for the loess deposits are reliable, a possible correlation exists between the dust record in the GRIP ice core and the magnetic susceptibility record of the Achenheim sequence. One argument which could help support the interglacial assignment of the Bt horizon would be the occurrence at its top of the Blake event, as documented in the Czech Republic (Brno event; Kukla, 1977). However, paleomagnetic investigations of the lower part of the Achenheim I pedocomplex show no reversal. However, the Blake event is very brief and could easily be missing from the record. Another argument to consider is the pedosedimentary budget. Although the TL measurements range between 83,300 ± 10,400 yr (maximum) and 72,500 ± 8700 yr (minimum), the pedosedimentary budget of the bottom of the sequence is similar to that of other loess sequences in northern France (Antoine *et al.,* 1994; Antoine *et al.,* in press) where TL ages underestimate the true age due to pedogenesis. This adds further support to our interpretation that the Bt horizon corresponds to the Eemian interglacial paleosol.

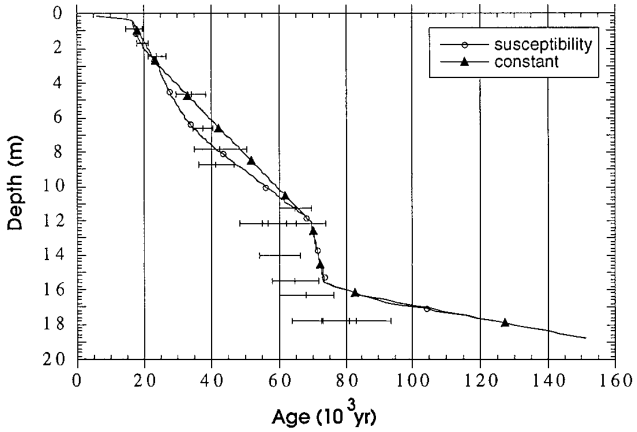

FIG. 3. Two age models for the last climatic cycle at Achenheim based on the TL dates (crosses with error bars) in this paper assuming constant sedimentation rate (triangles) and using susceptibility model (circles) following Kukla *et al.* (1988).

The lowest susceptibility values and highest dust flux occur in the top and bottom of the loess record (stages 2 and 4) and in the gray subunit. Such a pattern is in agreement with the ice-core records. The highest MS values in the loess occur during isotope stage 3, with readings lower than in MIS 5 (last interglacial soil). Another low dust interval in the ice record, designated as ice interstade 14, is correlated with the Glinde interstade (GRIP, 1993). This interval could correspond to the relatively high MS value at about 8 m depth in the Achenheim loess where the TL age is 41,500 ± 5100 yr. If so, it implies that the sedimentation at Achenheim was almost continuous between 70,000 and 16,000 yr ago.

Taking this interpretation into account, a time scale can be derived using a constant sedimentation rate in the loess record (model 1) or using susceptibility values as a measure of sedimentation rate (model 2) (Kukla *et al.,* 1988). Both models show similar results. However, the second model based on MS, and previously used in China, fits better within the framework of most of the TL dates in the Achenheim loess unit (Fig. 3). Although we are confident about this new chronology for loess deposition, the chronology of the bottom of the sequence is still speculative because of a possible hiatus and is depicted with a dotted line in Figure 4.

The comparison between variations in the MS signal at Achenheim and the GRIP dust record indicates that the major interstades pointed out in GRIP ice-core may be correlated with several oscillations during the last glaciation in the loess sequence (Fig. 4). They indicate that reliable correlations between Greenland and western European sequences can be proposed based on atmospheric dust and magnetic suscepti-

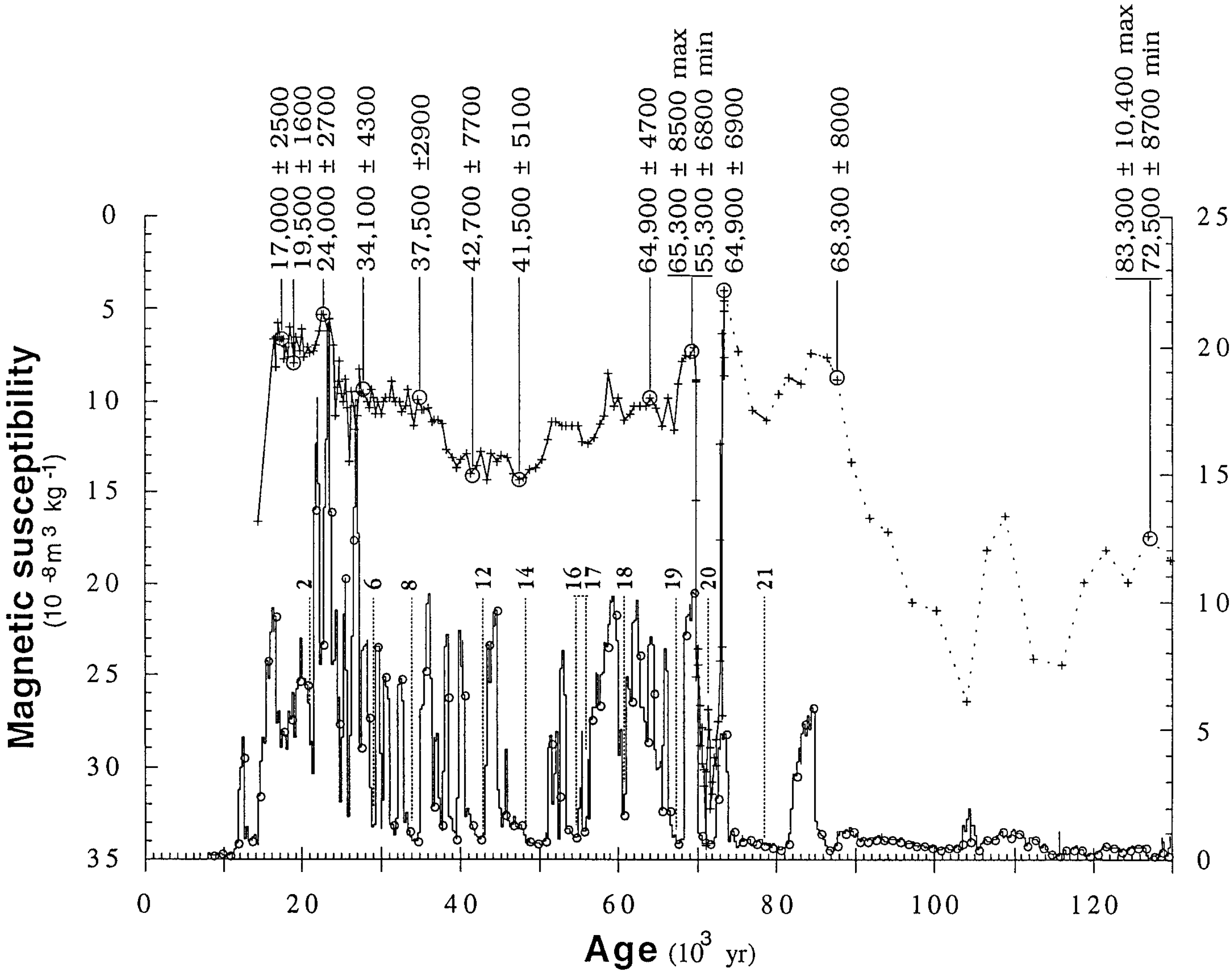

FIG. 4. Comparison between the low field magnetic susceptibility record at Achenheim (curve on right) and the GRIP ice-core dust record (curve on left) during the past 130,000 yr. Numbered ice-core interstades recognized in the GRIP (1993) record are shown for comparison with their possible equivalents in the loess sequence. The correlation of the bottom part of the Achenheim sequence below Marker II (ca. 65,000 yr) remains highly speculative because of a possible hiatus and is indicated by a dotted line.

bility. New luminescence and ^{14}C dating studies should help constrain the chronology and allow precise correlation between the Achenheim susceptibility variations and the Greenland dust record. Complementary investigations, at high resolution, focusing on the carbon isotopic content of the loess and the mollusk assemblages will permit improved interpretations of the interstadial sequence and may eventually permit correlations with the Dansgaard–Oeschger oscillations in the ice cores and Heinrich events in the North Atlantic Ocean.

CONCLUSIONS

The new magnetic susceptibility record of the last climatic cycle in the loess series at Achenheim indicates that this series is incomplete, especially in its lower part. A Marker subunit, which is interpreted as being related to dust storms of continental scale (Kukla, 1977), and the MS investigation show that loess deposition occurred during isotope stages 4, 3, and 2, consistent with the GRIP dust record. In both records, the intensity of dust storms was highest during MIS 4 and 2, and was lower during stage 3. The terrestrial equivalent of MIS 5 is represented by a lengthy hiatus after the development of an interglacial paleosol. A new chronology derived by correlating the loess series and the GRIP ice-core curve indicates that variations in MS are not a local phenomenon, but instead correspond to global events.

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