



# Magnetic Susceptibility Properties of Loess From the Willendorf Archaeological Site: Implications for the Syn/Post-Depositional Interpretation of Magnetic Fabric

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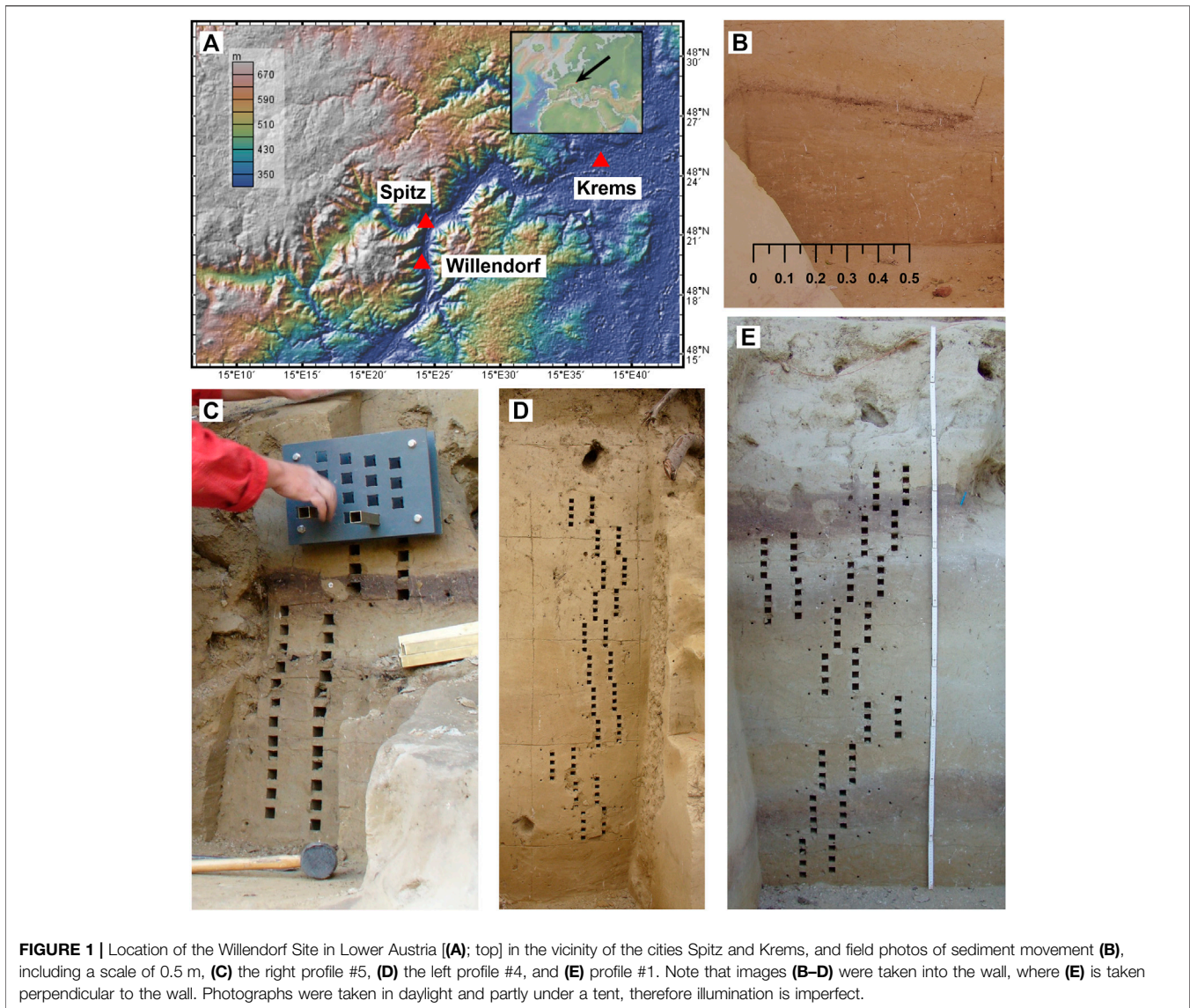
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At the Willendorf site Upper Paleolithic archeological layers associated to early Aurignacian cultures were found. The environmental conditions of the associated society, potentially co-existing with Neanderthal groups, is still not fully understood. Here, we report on environmental magnetic analyses including anisotropy of the magnetic susceptibility (AMS) carried out on loessic aeolian sediments at the Willendorf site. Data on lineation, foliation and the degree of anisotropy were used to assess depositional and post-depositional magnetic fabric properties and to deduce site-specific environmental processes. Overall, the loess is of aeolian origin and shows magnetic enhancement and magnetic fabric properties similar to those of other European loess geoarchives, but the magnetic mineralogy differs from many 'dry' loess sites, insofar as it shows a higher susceptibility during heating. We infer an enhanced neoformation of magnetite during heating due to the presence of organic matter. While at face value the AMS properties are indicative of pure aeolian loess consistent with previous studies, imbrication suggests post-depositional slope movement toward the Danube, which obscures inferences on palaeo-wind direction. It is well possible that these post-depositional magnetic fabric alterations occur at other localities with similar geomorphological settings.

**Keywords:** environmental magnetism, geoarchaeology, sedimentology, loess, magnetic fabric (AMS), magnetic fabric and anisotropy, rock magnetic analyses

## INTRODUCTION

Loess deposits provide the longest continuous terrestrial record of paleoclimatic change still accumulating today, and cover large parts of Eurasia. These sediments originate from settled dust of dominantly silty composition. Generally, fine and predominantly silty material can be derived directly from vast drylands or high mountain ranges, and is in the latter case transported first by river systems, and later on by wind (e.g., Cowie, 1964; Smalley, 1972; Mason, 2001; Smalley et al., 2009; Lancaster, 2020). In western Eurasia and especially in the surroundings of glaciated areas and river floodplains of (braided) rivers, silt-size mineral dust typically accumulates in sediment-traps close to the major rivers systems, where they contribute the substrate for loess-paleosol-sequences (LPS; e.g., Smalley, 1972; Smalley et al., 2009; Jipa, 2014; Lehmkuhl et al., 2016; Lehmkuhl et al., 2018). This may include the slopes of surrounding mountains. While aeolian sedimentation rates and pedogenetic



overprinting of accumulated dust may differ with climatic conditions, LPS often constitute high-resolution geoarchives of past environmental conditions where other archives are sparse or even absent (e.g., Derbyshire, 2003; Shi et al., 2003; Rousseau et al., 2007; Yang and Ding, 2014; Haesaerts et al., 2019). Therefore, numerous loess sites in Europe are considered valuable archives for past climate and environments (e.g., Shi et al., 2003; Antoine et al., 2009; Krauß et al., 2016; Moine et al., 2017; Obreht et al., 2017; Zeeden et al., 2018). This includes specifically archaeological sites imbedded in loess in Austria (e.g., Hambach et al., 2008; Händel et al., 2009; Sprafke et al., 2013; Terhorst et al., 2013, Terhorst et al., 2015; Zeeden et al., 2015; Meyer-Heintze et al., 2018; Sprafke et al., 2020). Notably in western Eurasia, loess hosts and preserves a wealth of archaeological materials due to its naturally high carbonate content which ensures not only bone preservation but generally buffers pervasive chemical weathering (Händel et al., 2009; Neugebauer-Maresch et al., 2014).

Sedimentological and rock magnetic analyses are used in geoarchaeological research in order to investigate the intensity and type of deposition, pedogenesis and post-depositional alterations (e.g., Hambach et al., 2008; Antoine et al., 2009; Zeeden et al., 2009; Böskén et al., 2018). The homogeneity of a sediment source may be determined from grain size-, geochemical- and rock magnetic properties (e.g., Cheng et al., 2019; Obreht et al., 2019). The intensity of pedogenesis may be derived from geochemical weathering indices (e.g., Buggle et al., 2011; Újvári et al., 2014; Obreht et al., 2019), the neoformation of clay (Schulte and Lehmkuhl, 2018) and also magnetic enhancement (e.g., Heller and Tung-Sheng, 1986; Forster et al., 1994; Forster et al., 1996; Hambach et al., 2008; Bradák et al., 2011; Zeeden et al., 2016). Post-depositional alteration through water logging may be derived from the depletion of magnetic minerals if present (e.g., Bábek et al., 2011; Baumgart et al., 2013; Gocke et al., 2014; Taylor et al., 2014; Krauß et al., 2016). In addition, the translocation of

fine magnetic particles may play a role (e.g., Oldknow et al., 2020).

At Willendorf, the sediment is described to be of local aeolian origin due to its grain size distribution properties (Haesaerts, 1990). The sediment exhibits clear features of slope movement (Haesaerts, 1990; Haesaerts and Teyssandier, 2003; Nigst, 2006; Nigst et al., 2008; Nigst et al., 2014), also **Figure 1B**. The loess shows stratigraphical consistency of bleaching, pedogenesis of different intensity, and charcoal indicative of (human?) burning. To assess in which manner the loess is suitable for paleoenvironmental reconstructions, we conducted an environmental magnetic study. Several rock magnetic parameters were measured to assess the type of magnetic enhancement or depletion, and to roughly characterize the minerals contributing to the magnetic susceptibility. Most relevant, the anisotropy of the magnetic susceptibility (AMS) was measured for a suite of samples to gain insight into magnetic fabric and either depositional or post-depositional processes. In order to account for possible spatial differences, several profiles were sampled. The AMS describes the spatial anisotropy of the magnetic fabric. In sediments, oblate fabrics often dominate due to the settling of, among others, clay minerals; the resulting oblateness is commonly called foliation (F). A preferential alignment, called lineation (L), may be interpreted in terms of transport direction, and/or may give insight into post-depositional processes, especially slope movement. Importantly, the AMS can give insight different depositional processes, such as aeolian loess and water-lain material (Liu et al., 1988; Bradák and Kovács, 2014). However, the values reported in Liu et al. (1988) are not ubiquitously applicable (Bradák and Kovács, 2014; Cheng et al., 2019). Further, preferential alignment directions of magnetic particles can be used to investigate the direction in which deposition took place (Jordanova et al., 2007b; Zeeden et al., 2015) and also the effects of post-depositional alteration (e.g., Bradák and Kovács, 2014; Taylor and Lagroix, 2015; Bradák et al., 2019a).

Here we present a rock magnetic study on the Willendorf site in Austria, which is famous for reports on the oldest Aurignacian technology in Central Europe (Nigst et al., 2008; Nigst et al., 2014). The key aim is to understand the primary (post) depositional and pedogenic processes.

## SETTING

The archaeological site of Willendorf is famous for the “Venus of Willendorf” (Antl-Weiser, 2009). It is one of a suite of archaeological sites preserved in loess along the Danube in the area since 2006, systematic excavations were conducted by an interdisciplinary team (Nigst, 2006; Nigst et al., 2008; Nigst et al., 2014), from which one of the earliest modern human tool assemblages in western Europe was identified. The excavation studied here is commonly referred to as “Willendorf II.” The Willendorf II section is located in the Danube valley west of Vienna (Austria) in the Wachau area (**Figure 1**). The exposure is located on a terrace c. 15 above and c. 300 m west of the present Danube river at 48°19'23.5" latitude and 15°24'15.2" longitude.

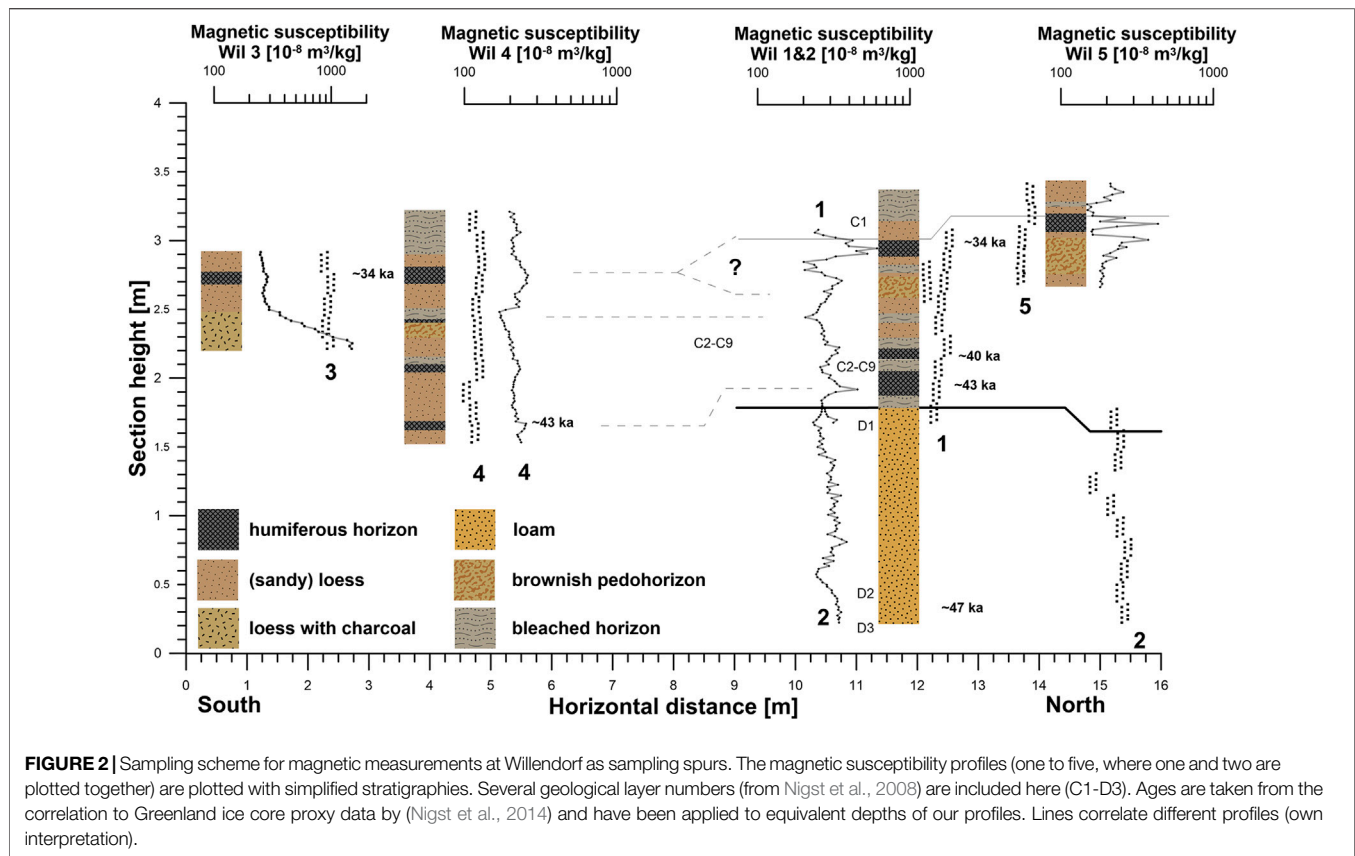
Along with the archaeological excavations, sedimentological investigations and detailed <sup>14</sup>C dating have been carried out. Several publications divide the site into sedimentological Units A (top) to E (bottom) (Haesaerts, 1990; Haesaerts et al., 1996; Haesaerts and Teyssandier, 2003, and references therein). We sampled the Units C and D in order to gain information on the site formation and post-depositional processes. Unit D is characterized as “thick stony heterogeneous brown loam” (Haesaerts and Teyssandier, 2003). Abundant molluscs, a polyedric structure and biogalleries filled with carbonates are reported from the top of Unit D. It was <sup>14</sup>C dated to ~41,700 and ~39,500 BP. Layers (C9 to C2) represent a suite of yellow to gray loess intercalated with several humic horizons. The uppermost humic soil horizon (at the top of the interval C9 to C2; **Figure 2**) is expressed as strongest soil. Especially as the lower part is reported to be stretched by solifluction, and contains stripes of ash. Subunit C1 represents a tundra gley and represents a marker between the middle and late Pleniglacial at ~28,000 BP (Haesaerts, 1990; Haesaerts and Teyssandier, 2003). The layers at the archaeological site are inclined toward the Danube valley (Haesaerts et al., 1996; their **Figure 1**) and show, at least in part, signs of solifluction (Haesaerts, 1990; Haesaerts et al., 1996; Haesaerts and Teyssandier, 2003; Nigst et al., 2008; Nigst et al., 2014). Grain size distributions of the Willendorf stratigraphy are reported in Haesaerts (1990), and show the highest contributions of silt in the ~10–80 μm range. An additional coarse component (>150 μm) contributes up to ~10% in Unit D, but less than 5% to samples from Unit C. Haesaerts (1990) interprets the grain size data (in context of field observations) as indicative aeolian transported fluvial sediments from the Danube River floodplain.

Here we report on the sedimentological findings from environmental magnetic investigations, and contextualize these regarding selected loess geoarchives. Sedimentological descriptions of Willendorf were done by Haesaerts and Teyssandier (2003) and the references therein. Especially the paper by Haesaerts and Teyssandier (2003) provides comprehensive sedimentological descriptions of loess, loam and different soil types. In addition, their work and the paper by Haesaerts (1990) place the Willendorf into the stratigraphic context of other archaeological sites from the Danube Valley and Moravia.

## METHODS

Oriented specimens were taken using brass tubes and an orientation holder. The samples are cubes with an edge length of 2 cm each, giving 8 cm<sup>3</sup> sample volume. Full spatial orientation was provided by means of magnetic compass measurements. The vertical spacing of sample centers was ~2.1 cm. Stratigraphic heights are given in cm as relative to the profile base.

Once in the laboratory, samples were stored in a μ-metal box until measurements began. Measurements were carried out in the Laboratory for Paleo- and Environmental Magnetism, Bayreuth. Anhyseric remanent magnetisations (ARMs) were produced along one spatial axis, and were induced with a 50 μT static



field and 100 mT alternating field amplitude using a Magnon AFD 300 (Figure 3). Isothermal remanent magnetisations (IRMs) were induced with fields up to 2.5 T using a MAGNON PM II pulse magnetizer. Back-field IRMs were produced to determine the coercivity of remanence ( $B_{cr}$ ). The magnetisations resulting from imprinting ARMs and IRMs were measured using an AGICO JR-6A spinner magnetometer.

The mass-specific magnetic low-field susceptibility (MS) and AMS measurements were made with an AGICO KLY-3S kappabridge at a frequency of 875 kHz and a magnetic field intensity of 300 A/m. The temperature dependent susceptibility ( $\kappa$ -T) was determined with this bridge and the CS-3 furnace under an Argon atmosphere. Data were corrected for a nine-point moving average smoothed dataset of the empty holder, and were scaled to the mass-normalized room temperature susceptibility using the CUREVAL software supplied by AGICO. The frequency dependent susceptibility ( $\chi_{fd}\%$ ) was measured for profiles one to three. A MAGNON VFSM was used with frequencies of 300 Hz and 3 kHz and a field of 300 A/m.  $\chi_{fd}\%$  is defined as  $(\chi_{300\text{ Hz}} - \chi_{3\text{ kHz}}) / \chi_{300\text{ Hz}} \times 100$ ,  $\Delta\chi$  represents the difference  $\chi_{300\text{ Hz}} - \chi_{3\text{ kHz}}$  (Figure 4).

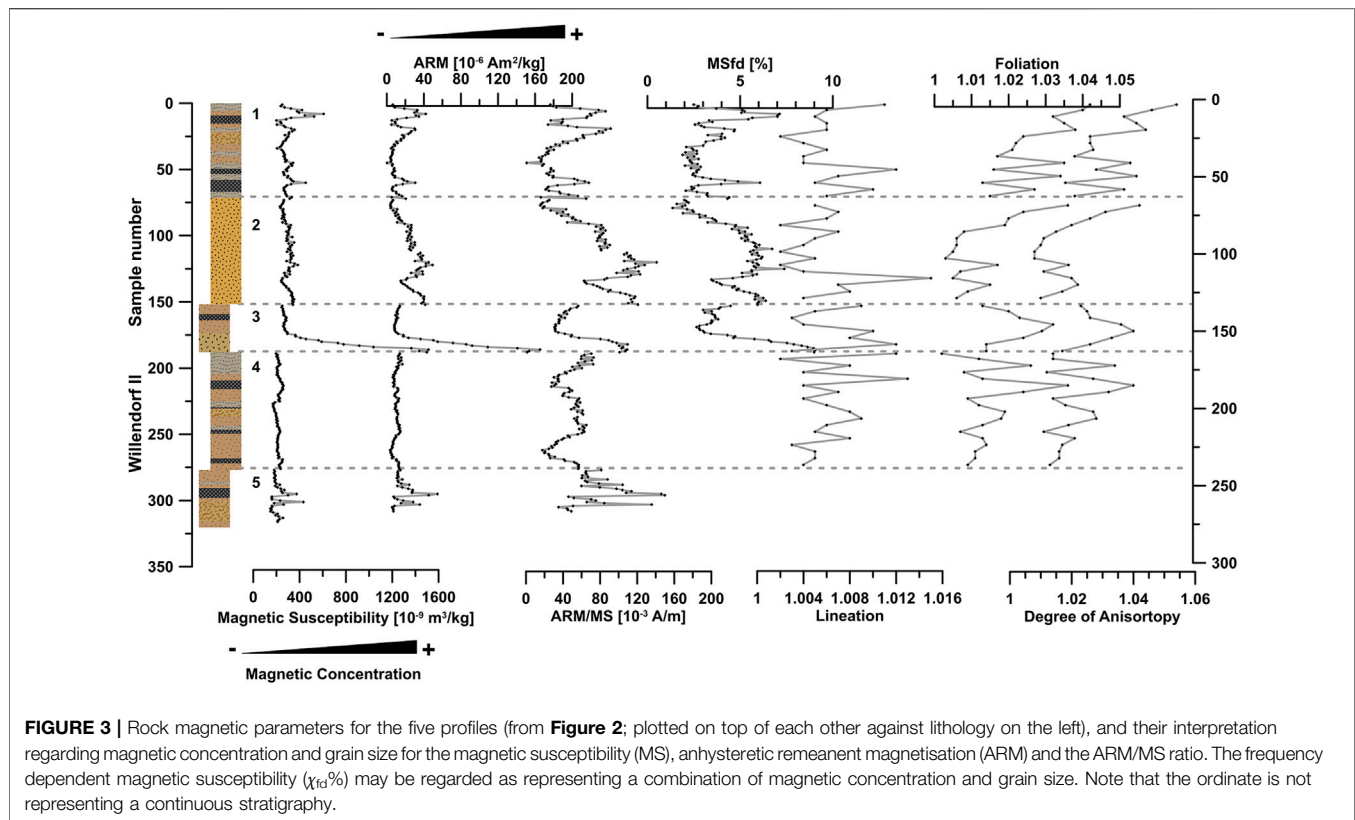
The AMS was measured for every 8th/5th sample. The AMS is defined by a symmetric tensor with three principal axes ( $k_1 > k_2 > k_3$ ).  $k_1$  is the main MS axis of a 3-dimensional ellipsoid and represents the magnetic lineation direction.  $k_3$  is perpendicular to the magnetic foliation which represents a plain through  $k_1$  and  $k_2$  (e.g., Ferré et al., 2003). The principal susceptibility angles were

corrected for the sampling angles, and were calculated together with AMS parameters using the AGICO software Anisoft 5.0. The determination and interpretation of AMS is a useful tool to determine the alignment of para- and ferromagnetic particles. Both the intensity of alignment and its direction can give insight into syn- and post-depositional sedimentary processes. However, a single sample may not be representative for a past environment, and commonly multiple samples are being investigated for a well-founded interpretation (Tarling and Hrouda, 1993). The AMS parameters lineation (L), foliation (F) and the degree of anisotropy (P) are plotted in Figure 3 with corresponding depths. These are defined as  $L = (k_1 - k_2) / k_{\text{mean}}$ ,  $F = (k_2 - k_3) / k_{\text{mean}}$  and  $P = k_1 / k_3$  (Tarling and Hrouda, 1993, and references therein).

## RESULTS AND DISCUSSION

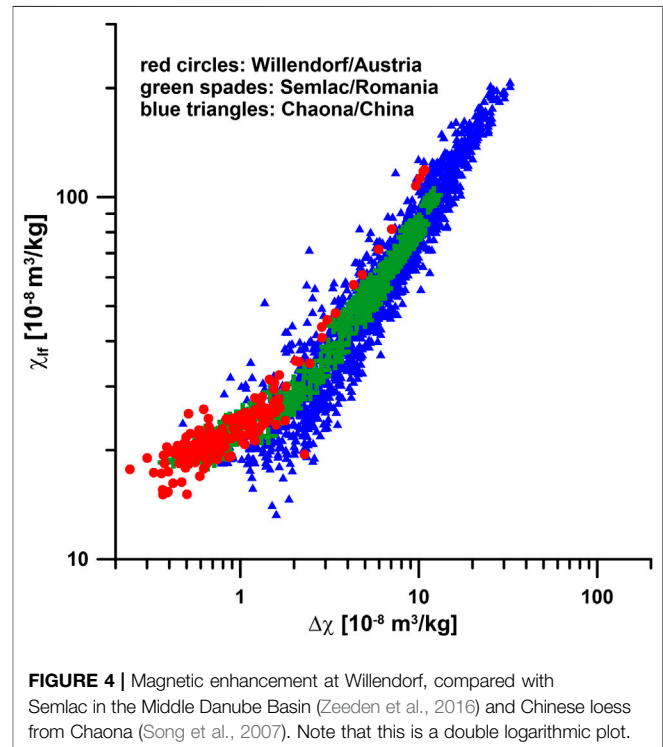
### Rock Magnetic Properties as Indicators of Lithology

The reported rock magnetic datasets, in depth, consist of the magnetic susceptibility, its frequency dependency, and the ARM. In addition, AMS,  $\kappa$ -T and IRM data have been measured for selected samples (Figures 3, 5–7). An overview of the sampling scheme is given in Figure 2, with MS data plotted for all samples. Figure 3 depicts several rock magnetic properties (left) and also the AMS properties: Lineation and Foliation (right). The

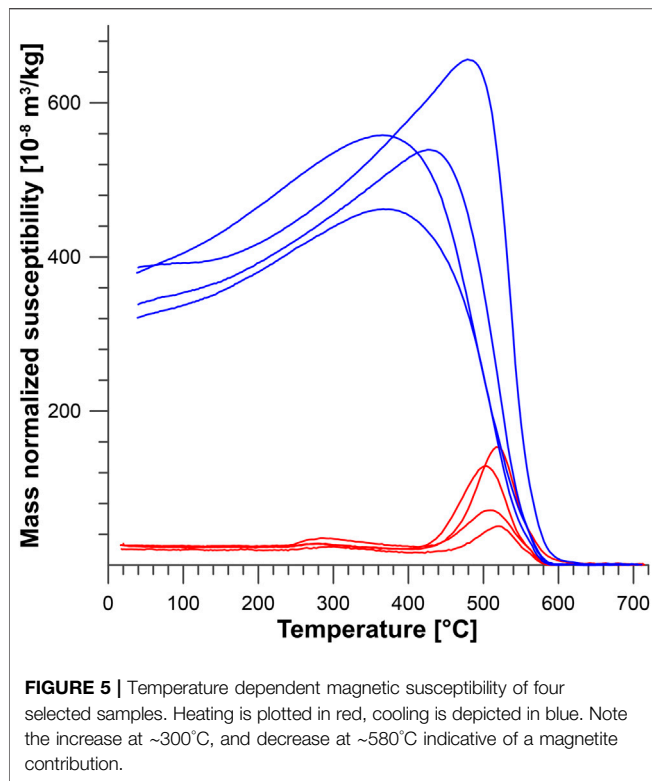


magnetic parameters ARM, ARM/MS and  $\chi_{fd}\%$ , indicative of magnetic concentration and grain size, roughly follow the lithology. Increased values of the MS,  $\chi_{fd}\%$ , and ARM occur in soil formation phases and cultural layers. The mean MS is  $29.5 \times 10^{-8} \text{ m}^3/\text{kg}$ , the mean  $\chi_{fd}\%$  is 4%, and the mean ARM is  $18.63 \times 10^{-8} \text{ Am/kg}$ .

Mineral magnetic parameters have been recognized as relevant paleoclimate proxies in loess research. MS and  $\chi_{fd}\%$  provide highly sensitive proxies in particular for humidity during dust accumulation and loess formation (e.g., Buggle et al., 2014 and references therein). This is based on the assumption that the original loess can be regarded as homogenous, and the neoformation of magnetic minerals (mainly magnetite and maghemite) is driven by pedogenesis. Increasingly intense pedogenesis enhances the mineral magnetic signals. The MS of any mineral magnetic assemblage in loess-paleosol sequences is also determined by the physical grain size distribution and magnetic mineralogy. The highest values in MS and  $\chi_{fd}\%$  can occur in intervals with higher concentrations of ultra-fine magnetic particles, but may in theory also be dependent on dust source and wind intensity (Song et al., 2010). Such fine particles precipitate dominantly from weathering solutions, and their abundance is a sensitive sediment/soil humidity proxy (e.g., Balsam et al., 2011; Maher, 2011). The MS is mainly an indicator of bulk concentration of magnetic minerals, while the  $\chi_{fd}\%$  is mainly driven by magnetic grain size. Increased  $\chi_{fd}\%$  indicates fine-viscous (VF herein) magnetic grain sizes in the transition from Stable Single Domain (SSD) and Superparamagnetic (SP)



states (e.g., Zheng et al., 1991; Yu and Oldfield, 1993; Deng et al., 2006).



The IRM acquisition curves show the dominance of magnetically soft minerals (Figure 7), here probably magnetite and maghemite. A hard component, which is not fully saturated at 2.5 T, is also present, and is interpreted to represent (goethite and/or) hematite. The ARM signal is considered to be driven by the concentration of ferromagnetic particles. Thereby, ARM reflects mainly Stable Single Domain (SSD) magnetite and maghemite, for which MS is relatively low. Consequently, the ARM/MS ratio is related to magnetic grain size, with higher ARM contributions (and thus a higher ARM/MS ratio) referring to magnetic grain sizes of SSD and small PSD range (c. 0.03–0.2  $\mu\text{m}$ ; Liu et al., 2012). This relationship between ARM contribution and grain size is highlighted by the pattern similarity of the ARM and the  $\chi_{fd}\%$ , which is also related to magnetic grain size. The information from both proxies characterize the enhancement of fine magnetic grain size populations at the SP-SSD boundary, which is increasing with pedogenetic overprinting of unaltered aeolian dust accumulation.

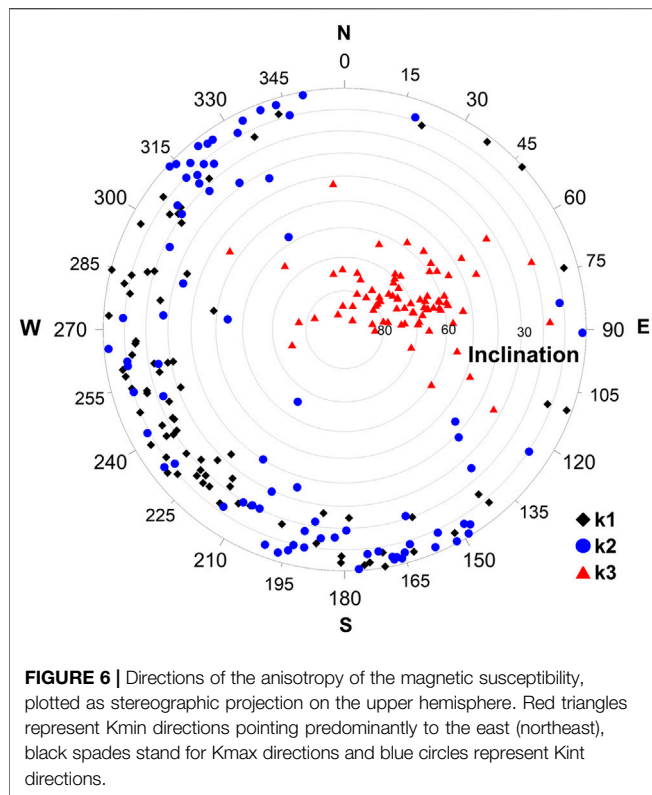
Although the frequency dependency of the magnetic susceptibility is relatively low on average, a magnetic enhancement similar to other Eurasian profiles can be observed (Figure 4). For example, the magnetic enhancement at Willendorf is similar to the enhancement at Smlac (eastern Middle Danube Basin; Zeeden et al., 2016) and Chaona (Chinese Loess Plateau; Song et al., 2007). The highest MS and  $\Delta\chi$  data from Willendorf are likely related to a contribution of magnetic minerals created during burning in an archaeological and pedo-horizon in sub-profile three (vgl. Figure 2). In the enhancement plot (Figure 4), data from Willendorf show a higher increase of MS than of  $\Delta\chi$ . This property suggests a higher proportion of SSD

and MD particles with high MS but limited VF particles. This may also be an influence of higher hematite concentrations; its presence is indicated by the hard IRM component.

## Magnetic Mineralogy Derived from Temperature Dependent Magnetic Susceptibility

To gain insight into the magnetic mineralogy of the Willendorf site, high-temperature susceptibility experiments were carried out. Figure 5 shows the results of high-temperature susceptibility measurements (normalized to the initial susceptibility) from selected samples. The results are similar for the four investigated samples and are therefore discussed together.

Little change can be observed in the magnetic susceptibility during heating up to ~240°C, but an increase in the magnetic susceptibility is present from ~250 to ~280°C. This pattern is followed by an MS decrease up to ~400°C, a strong increase to ~500–520°C, and a final decrease in the susceptibilities at ~580–600°C (Figure 5). Oches and Banerjee (1996) discuss an increase in the magnetic susceptibility at ~300°C as related to a “transition of weakly-magnetic Fe-hydroxides (e.g., lepidocrocite) to maghemite or some other higher susceptibility phase”. The decrease between ~300 and 400°C has been interpreted as the alteration of maghemite to hematite (Gao et al., 2019 and references therein). The increase from ~400 up to ~510°C is interpreted as formation of magnetite from several other iron bearing minerals (Hunt et al., 1995; Oches and Banerjee, 1996; Deng et al., 2001; Liu et al., 2005; Deng et al., 2006). The sample with the highest MS also shows an increase beyond this temperature, which may be a contribution of the Hopkinson effect (Dunlop, 2014). However, due to the decrease in MS before ~550°C and a strong increase of the MS during heating we consider the Hopkinson effect a contributor, but not the dominant control on MS above ~450°C (following Deng et al., 2000). Also the increased MS during cooling speaks for the neo-formation of magnetite, and against the dominance of the Hopkinson effect. Here, the final decrease of the susceptibility at ~580°C is interpreted to represent the Curie temperature of magnetite. While it is clear from these data that magnetite dominates the magnetic susceptibility, the size of the potential contribution from hematite is uncertain in this case. The fact that magnetite did only partly oxidize to maghemite during seasonal dry phases may be interpreted as annually mostly wet soil and sediment conditions, possibly due to periglacial conditions. Note that our  $\kappa$ -T results are similar to the  $\kappa$ -T data obtained from loess from the last glacial at the Krems-Wachtberg archaeological site about 20 km north-east of Willendorf (Zeeden et al., 2015), a loess-paleosol sequence in the Czech Republic (Oches and Banerjee, 1996), and the Poiana Cireşului site in eastern Romania (Zeeden et al., 2009, Zeeden et al., 2011); and as such, indicates similarities in terms of magnetic mineralogy. However, in other studies of European loess distinctly different temperature dependent susceptibility patterns have been observed in the drier parts of the Middle and Lower Danube Basins (Jordanova et al., 2007a; Necula and Panaiotu, 2012; Bradák et al., 2019b). In particular, the strong



increase in MS from  $\sim 450$  to  $580^\circ\text{C}$  is not present in loess preserved within arid and steppe environments. This increase in MS from  $\sim 450$  to  $580^\circ\text{C}$  may be related to a higher amount of organic matter in the sediment at Willendorf (Campbell et al., 1997).

A relevant contribution of water logging processes would lead to an increase in the amount of fine particles through grain size reduction. This would be visible as increasing  $\Delta\chi$  and decreased MS in **Figure 4** (Baumgart et al., 2013; Zeeden et al., 2018). However, this has not been observed in our results. Water logging can also increase magnetic grain size through preferential dissolution of small grains (e.g., Oldknow et al., 2020). This would lead to decreasing  $\Delta\chi$  with decreasing MS, which does not seem a relevant factor either compared to reference data (**Figure 4**).

## AMS Properties

Phyllosilicates (here probably micas and clay minerals), generally have oblate AMS ellipsoids (e.g., Borradaile and Werner, 1994; Martín-Hernández and Hirt, 2003). Under gravity these will settle preferentially in a horizontal plane, imprinting an oblate magnetic fabric in the bedding plane. Also compaction plays a role and increases F (Zhu et al., 2004). Since the AMS of most samples from Willendorf is oblate due to the higher foliation than lamination (**Figure 3**), and only few samples show strong laminations, the AMS may be dominated by phyllosilicates and potentially by super-fine ferrimagnetic particles incorporated in and attached to those minerals (Hyodo et al., 2020).

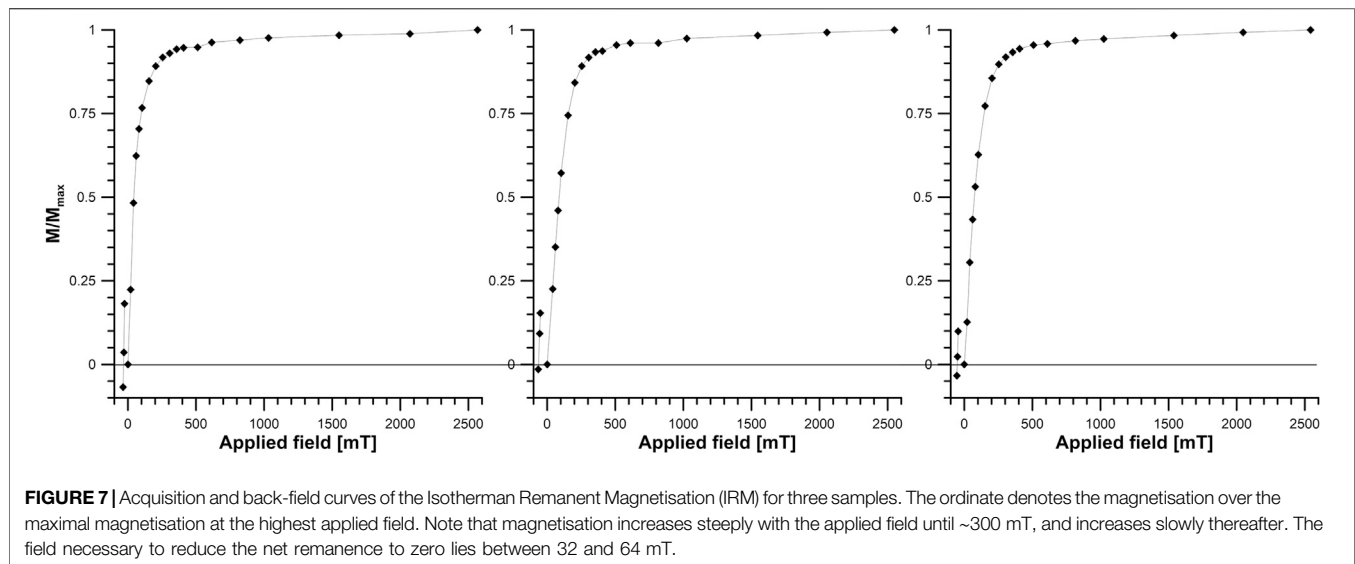
Here, the measures of anisotropy (P, L, F) show no obvious trends and relations to archaeological layers and pedo-

horizons. Generally, the anisotropy of samples is low, mean values for P, L and F are 1.006, 1.017 and 1.023, respectively. The P and F data correlate with a correlation coefficient of 0.98, whereas the correlation between the L and F is only 0.01. The F and L are independent variables, and therefore may have different physical and genetic origins. Foliation is commonly found parallel to the bedding plane due to gravitational forces and compaction (Hus, 2003), and is generally interpreted to be the result of sedimentation of oblate particles. Wang and Løvlie (2010) suggest that the foliation is mainly acquired during (initial) wetting of freshly aeolian deposited loess.

The lamination of the magnetic fabric may be related to a preferential aeolian wind or deposition direction (e.g., Tarling and Hrouda, 1993; Lagroix and Banerjee, 2002; Zeeden et al., 2015), or can originate from post-depositional processes (e.g., slope movement processes; Reinders and Hambach, 1995). At Willendorf, slope movement toward the Danube valley is evident in the field (**Figure 1B**). The imbrication of the  $k_3$  axis in the north-east direction (**Figure 6**) may be related to either deposition on a slope, or to post-depositional changes due to down-slope sediment movement. Because the magnetic foliation is mainly acquired through gravitational forces during initial wetting (Wang and Løvlie, 2010), we consider the imbrication as originating from post-depositional slope movement in the direction of the Danube valley. The  $k_1$  direction is aligned in the downslope direction with the imbrication of the  $k_3$  inclination. We therefore interpret the  $k_1$  direction as indicative of the direction of the windblown loess, while the imbrication as representing post-depositional slope processes, the latter dominating the AMS at Willendorf.

The degree of anisotropy has been suggested to reflect the depositional environment of loess and loess-like deposits, where aeolian loess has been shown to obtain a lower foliation relative to loess redistributed by water or as water-saturated mud [mostly  $<1.02$ , (Liu et al., 1988; Bradák and Kovács, 2014); mostly  $<1.03$  (Wang and Løvlie, 2010)]. Comparing the Willendorf data (mean Foliation F of 1.023 and mean Lamination L of 1.017) to the data of Bradák and Kovács (2014), Liu et al., (1988), and Wang and Løvlie (2010), the loess at Willendorf is of aeolian origin, and not re-deposited on the slope by periglacial or other slope processes. This contradicts our interpretation of a post-depositional imbrication. In addition, the loess was deposited on a slope which makes the absence of post-depositional relocation unlikely, especially also regarding potential sediment dynamics under a periglacial climate. Therefore, this study shows that the low foliations may not always be representative of “purely” aeolian loess. We hypothesize that the values of AMS properties are influenced by the grain size distribution, which is in this case rather coarse. Especially the addition of quartz sand can be expected to decrease the AMS and lead to a lower foliation than caused by finer silt- and clay-sized (and more often platy) particles.

While fine magnetic particles formed during *in-situ* pedogenesis may dominate the MS signal, the originally deposited carriers of MS are relevant for interpreting the AMS. This may be a large or small proportion, depending on the original contribution of grain sizes. Numerous studies have



shown a relationship between particle size and magnetic grain size, with detrital magnetic grains being SSD or coarser. These tend to reside in coarser particle size fractions—and therefore, are less liable to translocation. Larger detrital (magnetic) grains are unlikely to be moved within the sediment, while small grains may move downward in the sediment column. In addition, illuviation of fine particles (as fine clay), which may be relevant carriers of fine magnetic particles, can be excluded here because the sediment has a high carbonate content throughout, preventing any illuviation processes (e.g., Kühn et al., 2018).

## CONCLUSION

Based on the magnetic properties of the loess sediment at Willendorf, we draw the following conclusions on the sedimentation and post-depositional alteration.

Grain size data demonstrated the loess to be of aeolian origin. The loess is partly overprinted by pedogenesis, but interstadial soils are much more weakly developed than interglacial soils from the reference data, in agreement with chronological information. The magnetic sediment properties do not show magnetic depletion due to waterlogging and/or permafrost action which is surprising in light of the presence of leached horizons, but may have resulted from the presence of high carbonate content which could have buffered dissolution reactions.

Despite evidence for colluvial slope processes in the field, these do not result in enhanced foliation values. Rather, the relatively low foliation values observed are controlled by the grain size of the loess, provenanced from deflation of the nearby Danube floodplain. We imply that AMS is to be seen in the context of grain size of the investigated material, and that general distinctions between aeolian and water-lain fabric can only be made for specific grain size distributions. The lineation in the southwest/northeast direction is interpreted as indicative for deposition on a gentle slope inclined toward the Danube. In particular, we interpret the clear imbrication in the same

direction as the result of post-depositional processes moving the sediment toward the valley, presumably under a periglacial climate with seasonal freezing and thawing cycles.

## DATA AVAILABILITY STATEMENT

The original data presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

UH designed the study; CZ and UH took the samples; CZ carried out measurements and carried out the study. Both authors jointly interpreted data. CZ wrote the manuscript with input from UH.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feart.2020.599491/full#supplementary-material>.



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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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