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Does timing or location matter? The influence of site variability and short-term variations in precipitation on magnetic enhancement in loessic soils

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ABSTRACT

The magnetic properties of soils are often used to quantify soil development and reconstruct past climates in regions where other recorders of paleoclimate are unavailable. Soil-based paleoclimate reconstructions rely on transfer functions that link soil-magnetic properties to the climatic conditions during pedogenesis. Recently, the reliability of these transfer functions has been discussed, but the variability of soil magnetic properties at a given site is poorly known. This study analyzes multiple cores of a loessic soil that have been collected at one locality over the timespan of five years. An extensive magnetic characterization of these cores shows that the soil magnetic signal and any climate proxies derived from magnetic data are reproducible between cores from one site and do not depend on short-term (annual or seasonal) fluctuations in precipitation. Therefore, the observed scatter in existing soil-climate transfer functions is likely due to variation in microclimates, soil drainage, and pedogenesis processes. Rather than sampling existing sites multiple times, existing transfer functions are best improved by careful site selection that controls non-climate-related soil forming factors as well as possible.

1. Introduction

Soil magnetic properties are often used in the reconstruction of past climates. Well-developed soils are generally magnetically enhanced, i.e. their upper soil horizons (A- and sometimes B-horizons) are more magnetic than the underlying parent material (e.g., Dearing et al., 1996b; Heller and Liu, 1984; Maher, 1988). Soil magnetic measurements can quantify the abundance, grain-size and mineralogy of these magnetic phases (e.g., Banerjee et al., 1981; Geiss and Zanner, 2006; Maher, 1986; Thompson and Oldfield, 1986), and this information can be used as a paleoclimate proxy (e.g., Geiss and Zanner, 2007; Maher and Hu, 2006; Maher et al., 2002). Soil-based climate reconstructions are especially valuable in mid-continental regions, where other recorders of paleoclimate (e.g., lake sediments) are unavailable.

The magnetic enhancement in well-developed soils is due to the increased abundance of fine, stable single-domain (SSD) and ultra-fine superparamagnetic (SP) ferrimagnetic particles (magnetite and/or maghemite). Such an increase can be caused by the preferential removal of weakly-magnetic components, such as carbonates or clays, from the upper soil horizons (Singer and Fine, 1989), the addition of natural (e.g., Kukla, 1988) or man-made (e.g., Blundell et al., 2009; Hanesch et al., 2007) magnetic particles, or the neoformation of ultrafine ferrimagnetic particles when the soil is exposed to the heat of intense fires (e.g., Le Borgne, 1960; Oldfield and Crowther, 2007) or subjected to repeated changes in soil moisture (e.g., Maher and Taylor, 1988; Orgeira et al., 2011; Torrent et al., 2010).

Past studies have used the magnetic properties of modern soils to establish transfer functions between magnetic enhancement and climate (Geiss and Zanner, 2007; Heller and Liu, 1986; Maher and Thompson, 1995; Maher et al., 2002) and used these transfer function to reconstruct past rainfall regimes (e.g., Maher and Thompson, 1995). Recently, the errors associated with such transfer functions have been investigated in more detail (Heslop and Roberts, 2012; Maher and Possolo, 2013). What has not been addressed is the temporal and spatial variability of magnetic properties at a given study site or pedon (e.g., Campbell and Edmonds, 1984; Johnson, 1963).

Magnetic susceptibility, a commonly used parameter to estimate the concentration of strongly magnetic minerals, is highly dependent on the presence of ultrafine, superparamagnetic (SP) ferrimagnetic minerals ($d \ll 0.01$ μm), and frequency dependent susceptibility ($\chi_{FD}(\%)$) looks exclusively at these nano-sized iron compounds (Worm, 1998). While larger ferrimagnetic particles are likely to form over numerous wetting/drying cycles (for one model that describes such seasonal growth of ferrimagnetic minerals see Orgeira et al., 2011), ultrafine, nanosized iron oxides may form more rapidly. Therefore, annual changes in ultrafine iron-oxide particles may affect soil magnetic properties and introduce additional errors in soil-based climate reconstructions.

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This study analyzes several soil cores, sampled over five years, to better define the spatial and temporal variability of soil magnetic properties within a pedon. It tests whether short-term, annual climatic variability and small-scale spatial changes within a pedon significantly affect magnetic properties, estimates of magnetic enhancement, and hence, the interpretation of soils in terms of climate. It will also help in the interpretation of soil transfer functions. Currently these functions display a significant amount of scatter when relating modern climate to magnetic enhancement. This scatter may be due to year-to-year changes at a site, due to spatial variability within a site or due to unaccounted differences (for example in microclimate) between sites. By studying the magnetic properties of several cores taken over the span of several years from one site it is possible to isolate some of the causes of this variability and provide guidance on how to improve existing and future transfer functions.

2. Methods

Between 2002 and 2006 soil cores (with the exception of core PRA 03-A) were collected within meters of each other using a hydraulic, 3-in-diameter soil probe (Giddings Machine Co., Windsor CO). Core PRA 03-A was collected with a hand-operated 3-in-diameter soil auger. The cores were described in the field using standard procedures and terminology (Soil Survey Division Staff, 1993) and subsampled into small 4-oz plastic bags. Samples were averaged over a sampling interval of 5 cm for the uppermost meter and 10 cm for the remainder of the core. In the laboratory samples were air dried, gently crushed by hand and passed through a 2-mm sieve to homogenize the samples and to remove root and plant fragments. For magnetic analyses the samples were tightly packed into weakly diamagnetic plastic cubes with a sample volume of 5.3 cm^3.

Low-field magnetic susceptibility (χ) was measured for all samples using a Kappabridge Susceptibility meter (KLY-2 for 2002 samples, KLY4s for all others). Frequency-dependent susceptibility $\chi_{FD}(\%) = (\chi_{lf} - \chi_{hf}) / \chi_{lf} \times 100$ was measured using a Bartington MS3 susceptibility meter equipped with a MS2B dual-frequency sensor (averaging time = 5 s for each measurement). Low-frequency susceptibility (χ_{lf}) was measured at 0.47 kHz, whereas high-frequency susceptibility (χ_{hf}) was measured at 4.7 kHz. $X_{FD}(\%)$ often depends on small differences between two large numbers, which amplifies measurement errors. The error in $\chi_{FD}(\%)$ was initially estimated by averaging four susceptibility measurements for each frequency, and these four measurements were bookended by blank measurements to correct for instrument drift. However, the resulting error estimate for $\chi_{FD}(\%)$ neglects sometimes significant errors due to changes in sample placement with respect to the sensor. $\chi_{FD}(\%)$ was therefore remeasured for all cores. The sample was removed from the sensor between each measurement and each individual measurement was corrected for instrument drift. The two methods yield nearly identical results for $\chi_{FD}(\%) > 4\%$, but the second method is superior for samples characterized by low $\chi_{FD}(\%)$ values (<2%) in the B- and C-horizon samples. In general, only a very small grain-size range near the SP–SSD grainsize boundary influences χ_{FD}. For the Bartington MS2B dual-frequency sensor this range extends from approximately 19 nm to 21 nm (Hunt et al., 1995).

Remanent magnetizations were measured for all samples using a JR6 spinner magnetometer (AGICO Corp.) with a sensitivity of approximately 1×10^{-5} A/m (a conservative estimate when the instrument is used in low-speed mode) or approximately 1×10^{-8} Am^2/kg for the samples used in this study. Anhysteretic Remanent Magnetization (ARM) was induced using a Magnon International AFD 300 alternating field demagnetizer. The peak magnitude of the demagnetizing field was 100 mT; the magnitude of the bias field was 50 μT. Isothermal Remanent Magnetization (IRM) was induced in three field pulses of 100 mT provided by an ASC Scientific IM-10-30 impulse magnetizer.

The concentration-dependent parameters χ, ARM, and IRM can be used to estimate the absolute abundance of mainly ferrimagnetic minerals. The ARM-ratio (ARM/IRM) is used to estimate the relative abundance of small ($0.01\ \mu m < d < 0.1\ \mu m$) stable single-domain (SSD) particles (e.g., King et al., 1982; Thompson and Oldfield, 1986), while $\chi_{FD}(\%)$ is generally used as a proxy for the relative abundance of even finer superparamagnetic (SP, for magnetite: $d < 0.01\ \mu m$) particles (e.g., Dearing et al., 1996a; Worm, 1998). Increases in the abundance of magnetic minerals, combined with a fining of the magnetic grain-size distribution towards SSD and SP particles are commonly used to quantify the degree of pedogenesis (e.g., Fine et al., 1989; Kukla and An, 1989; Maher, 1986) and to reconstruct past environments (e.g.,Geiss et al., 2008; Heller and Liu, 1986; Maher and Thompson, 1995).

3. Study site

Prairie Pines is a small natural area near Lincoln, NE (40.8423°N, −096.5591°W). The site has been donated to the University of Nebraska and contains remnants of native prairie uplands and undisturbed loessic soils. The study site is located in the SE corner of the property (Fig. 1) on a flat, stable ridge top. The well-drained soil (originally Sharpsburg series, recently remapped as Aksarben series fine smectitic, mesic Typic Argiudoll USDA-NRCS, 2013, 2014) developed in upland prairie, but the site has become progressively overgrown by sumac, which intrudes from the fence line. Figure 1 b shows the site as it appeared in 2013. The parent material is Peoria loess, deposited during the Wisconsinan glaciation (~25–12 ka) (e.g., Mason et al., 2008). All studied cores were collected in brown to reddish-brown loess (10YR 5/3–5/4) on a very gently sloped surface (slope <2%), within the spatial resolution of the GPS-system used to locate the site (~10 m). The study by Geiss and Zanner (2007) contains a detailed description of the observed soil profile and the magnetic properties of a soil core sampled in 2002.

4. Precipitation history at the study site

The closest weather station to Prairie Pines is Lincoln, NE (HPRCC, 2013), which is located approximately 10 km west of Prairie Pines. The mean annual precipitation for Lincoln, NE is 760 mm/year, with most precipitation occurring during the summer months. Fig. 2 shows the departure from the long-term (1971–2000) mean for the time period between 2001 and 2007. Between 2001 and 2007 the site generally experienced drier than normal rainfall averages, but sampling in June 2003 and July 2005 occurred in months that received significantly more rainfall than normal.

5. Results and discussion

Fig. 3 shows simplified soil profile descriptions for all studied cores in comparison with the official description of the Sharpsburg series (USDA-NRCS, 2013). The thickness of the mollic horizon is consistent across all cores, varying between 30 cm and 50 cm, which agrees well with the official series description. Bt-horizon thickness is more variable: cores taken early in this study show relatively thin Bt-horizons with horizon thickness ranging between 36 cm and 44 cm, while cores obtained in 2005 and 2006 have thicker Bt-horizons with thicknesses ranging from 74 cm to 86 cm. Whether this change in horizon thickness is due to a change in soil descriptions or represents a true shift in profile properties is impossible to determine given that only small amounts of material are available for further study. Fortunately, as discussed below, the differences in Bt-horizon thickness do not affect the interpretation of the soil-magnetic data.

Fig. 3 includes bulk magnetic susceptibility (χ) data for each core. To allow for easier comparisons between cores, susceptibility data for a given core are shown with solid symbols and placed in front of a shaded gray area which displays the range of all susceptibility measurements at a given depth. Large values of χ indicate high concentrations of strongly-