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Magnetism From Atomic to Planetary Scales: Physical Principles and Interdisciplinary Applications in Geo- and Planetary Sciences

Key Points:

- Superparamagnetic magnetite in the sediments can be attributed to pedogenic soils
- Intensity of Human Impact in Northeastern China increases sharply at AD 1500

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A 1400 year environmental magnetic record from varved sediments of Lake Xiaolongwan (Northeast China) reflecting natural and anthropogenic soil erosion

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Abstract Lake sediments can provide high-quality information about human activities. In this study, we investigate a sediment core from Lake Xiaolongwan using magnetic and geochemical methods. The dominant magnetic minerals of this sediment core are stable single domain (SSD) and superparamagnetic (SP) magnetite particles. The increasing amount of SP particles reflected by the rise of magnetic susceptibility and frequency dependent magnetic susceptibility since AD 1500 can be attributed to an increasing influx in pedogenic soil, which is related to a regional-scale increase in the intensity of human activity in Northeastern China. This extends the timing of human activities, which is independent from climate changes and its effects on local ecosystems in Northeastern China significantly.

1. Introduction

There is a consensus that human activities can seriously affect ecosystems. This can result in a vegetation loss [Xiao *et al.*, 2013], soil erosion [Dearing *et al.*, 2015], decreased biodiversity [Jiang *et al.*, 2014], and air pollution [Yang *et al.*, 2010]. The deterioration of ecosystems, in turn, exerts increasing pressure on human society [Vitousek *et al.*, 1997]. To quantify the relationship between anthropogenic activities and environmental changes, it is essential to determine the development of human activities and its impacts on terrestrial ecosystems on longer time scales.

Northeastern China is located within the East Asian Monsoon region [Liu, 1985]. The vegetation cover in this region has been intensively disturbed in the recent past by logging and grazing [Chen, 2012]. Thus, the area is an ideal place to study the impact of human activity on the natural environment, e.g., soil erosion [Ye *et al.*, 2012]. So far, only a few studies have been carried out to investigate human activities during the mid to late-Holocene in Northeastern China [Makohonienko *et al.*, 2008]. In contrast, many investigations focused on the late-Quaternary paleoclimatic evolution [Chu *et al.*, 2004, 2009; Xu *et al.*, 2014].

Reconstruction of human activities can for example be carried out using historical documents [Ye *et al.*, 2009, 2012; Zhang *et al.*, 2011]. For instance, extensive migration in Northeastern China during the past 300 years is documented there [Ye *et al.*, 2009]. However, historical documents are often fragmentary and only reach back several centuries.

In contrast, natural archives are often continuous covering longer time scales. Lake and peat sediments for example are mostly well preserved and can provide high-quality information. On the basis of pollen data from peat sediments, Makohonienko *et al.* [2008] provided evidence for human impacts on the Jinchuan site in the Changbai Mountains (Figure 1), which is located within the mixed temperate broadleaved forest zone of Northeastern China since AD 1730. Nevertheless, the accurate timing and intensity of human activity in Northeastern China have not been well resolved due to chronological issues and uncertainties of the interpretation of paleoclimatic proxies [Li *et al.*, 2013; Panizzo *et al.*, 2013].

This study investigates varved sediments from Lake Xiaolongwan (XLW) with environmental magnetic and geochemical methods in a well-defined chronological framework. We aim to determine the history of

Figure 1. (a) Map indicating location of Lake Xiaolongwan (XLW) and other sites mentioned in the text (generated using DIVA-GIS 7.5, <http://www.diva-gis.org/>). (b) Aerial view of XLW and its forested catchment. (c) Bathymetric map showing the coring site (isobath intervals in meters).

human-environment-interactions and provide new insights into the timing and intensity of human activity in Northeastern China during the past millennium.

2. Study Area

Lake XLW (42° 18' N, 126° 21' E, maximum water depth = 15 m, elevation = 655 m asl) is located in the western part of Longgang, Northeastern China (Figure 1). XLW was formed by alkali basaltic phreatomagmatic eruptions in the late Pleistocene [Liu, 1999]. The surface and catchment areas of the lake are about 0.079 km² and 0.16 km², respectively.

The study area is influenced by the East Asian monsoon system. Cold and dry conditions prevail during fall and winter. In contrast, summer is warm and humid. The total mean annual precipitation is 760 mm and the mean annual air temperature is ~4°C [Chu et al., 2009].

3. Methods

Piston core X06 with a length of 695 cm was recovered from a water depth of 14.5 m in the early spring of 2006 (Figure 1). The varved sediments consist of gray- and brown- colored couplets [Chu et al., 2008]. The brown-colored layer formed in fall is mainly composed of dinoflagellate cysts [Chu et al., 2008], while the gray-colored layer, generated in spring and summer, consists of other organic, siliceous matter (plant detritus, diatom, chrysophyte cysts) and clastics [Chu et al., 2008]. Previous studies using scanning electron and optical microscopes, sediment traps, and independent chronologies indicate that the laminated sediments are most likely annually layered [Chu et al., 2008]. In this study, only the top 93 cm are presented. According to varve counting results the upper 93 cm contain 1415 couplets. Sediment accumulation rates (SAR) are calculated with a resolution of 100 years. The detailed chronology was adopted from previous studies [Chu et al., 2009, 2014; Xu et al., 2014].

The top 93 cm of core X06 were subsampled in 1 cm resolution (93 samples) which corresponds to a temporal resolution of about 27 years. In the summer of 2012, 24 soil samples were collected at 5 cm intervals from 85 to 30 cm in depth and 2 cm intervals from 30 to 0 cm in depth in a soil profile (N 42° 18.7', E 126° 35.2', 20 km away from XLW, Figure 1). Subsequently these samples were freeze dried and each sample was placed in a 2×2×2 cm³ plastic cube to conduct magnetic measurements. Low- and high-frequency

Figure 2. (a) Compound-specific $\delta^{13}\text{C}_{27-31}$ in the long-chain n-alkanes from XLW [Sun *et al.*, 2013]; (b) alkenone-based temperatures at Lake Sihailongwan which is 20 km to the east of XLW [Chu *et al.*, 2012]; (c) mass-specific magnetic susceptibility (χ_{if}) measured on sediments from XLW; (d) frequency-dependent magnetic susceptibility (χ_{fd} , error bar corresponds to 3 measurements); (e) Mean grain size (M_z) measured on sediments from XLW [Chu *et al.*, 2009]; (f) Chinese population development [Chen, 1997]; (g) accumulation rates of sediments from XLW (SAR); (h) varve thickness in the sediments from XLW; and (i) chronology of the upper part of sediment core X06 from XLW [Chu *et al.*, 2009], maximum age calculated for XLW by Chu *et al.* [2009] is used. The positions for representative samples used for rock magnetic measurements are marked with blue stars in figure 2c.

heating. χ -T curves were measured in an argon atmosphere using MFK-FA equipped with a CS-3 furnace with a maximum temperature of 700°C. Low temperature magnetic analysis discriminates magnetic mineralogies. In this study, a MPMS XL-5 magnetic measurement system was used to measure zero-field-cooling curves (ZFC). The detailed steps were as follows: Samples were cooled to 10 K in a zero field. Subsequently an IRM acquired at 2.5 T was measured during warming up to 300 K in the zero field with a temperature ramping rate of 5 K min⁻¹.

4. Results

4.1. Sedimentology, Geochemistry, and Physical Properties

The compound-specific $\delta^{13}\text{C}_{27-31}$ in the long-chain n-alkanes (Figure 2a) is sensitive to effective precipitation, and therefore represents a useful indicator for regional monsoonal precipitation [Chu *et al.*, 2014; Sun *et al.*, 2013]. An increase in $\delta^{13}\text{C}_{27-31}$ indicates less effective precipitation. $\delta^{13}\text{C}_{27-31}$ fluctuates around -31.5

mass-specific magnetic susceptibility (χ_{if} and χ_{hf}) was measured using a multifunction Kappabridge (MFK-FA) with frequencies of 976 Hz and 15616 Hz, respectively. Frequency-dependent magnetic susceptibility (χ_{fd}) was calculated as $\chi_{\text{fd}} = \chi_{\text{if}} - \chi_{\text{hf}}$ [Dearing *et al.*, 1996]. An anhysteretic remanent magnetization (ARM) was imparted with a Schonstedt GSD-1 alternating field (AF) demagnetizer with a peak AF of 100 mT and a superimposed direct bias field of 0.05 mT. Anhysteretic susceptibility (χ_{ARM}) is calculated through dividing ARM by the biasing field strength [Evans and Heller, 2003].

To characterize magnetic assemblages in representative samples, hysteresis loops, isothermal remanent magnetization (IRM) acquisition curves, and back-field demagnetization curves were measured and calculated the saturation magnetization (M_s), saturation remanence magnetization (M_{rs}), coercivity (B_c), remanent coercivity (B_{cr}), using a vibrating samples magnetometer (VSM 3900) with a maximum field of 1 T. First-order reversal curves (FORCs) were measured with the same device on selected samples with field increment of 1.15 mT, and processed with the FORCinel software v1.18 [Harrison and Feinberg, 2008]. They were used to determine signals of the magnetic domain and the coercivity spectrum of the samples [Roberts *et al.*, 2000].

Temperature-dependent magnetization curves (χ -T) characterize magnetic minerals and their alteration during

Figure 3. (a, e) Hysteresis loops, (b, f) FORC diagrams with a smoothing factor of 5, (c, g) temperature-dependent magnetic susceptibility curves, and (d, h) low-temperature demagnetization curves (ZFC) of selected samples from sediment core X06 from XLW.

‰ from AD 600 to AD 800, and around -31 ‰ since AD 800, demonstrating a relatively stable precipitation amount with somewhat dryer conditions since AD 800.

Figure 2b illustrates an alkenone-based temperature reconstruction for the growing season from varved sediments from Lake Sihailongwan (Figure 1) 20 km to the east of XLW [Chu *et al.*, 2012]. The temperature generally is stable except for some cold spells which occurred at AD 600–860, AD 1260–1300, AD 1510–1570, and AD 1800–1900.

Mean grain size (Mz) data from Chu *et al.* [2009] are shown in Figure 2e. It gradually increases from AD 600 to AD 1500. The increase accelerates at AD 1500 which is followed by more stable conditions on a high level since AD 1600. Chu *et al.* [2009] suggested that the trend of increased grain size during the last 300 years can be ascribed to an enhanced aeolian input of local origin.

Our results show that a significant shift in both SAR and varve thickness occurs in sediments of XLW at AD 1500 (Figures 2g and 2h). The SAR and varve thickness are often related to deforestation and agricultural land use [Zolitschka *et al.*, 2015], and can increase by an order of magnitude, as observed at Lake Holzmaar 2800 years ago [Zolitschka, 1998] and at Lake Belau 2200 years ago [Dreibrodt and Wiethold, 2015].

χ_{lf} can be used as a general indicator for minerogenic input [Dearing *et al.*, 2015; Haberzettl, 2015; Kastner *et al.*, 2010; Sandgren and Snowball, 2001]. From AD 600 to 800 χ_{lf} shows stable values around $7 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ and increases to $12 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ around AD 800 (Figure 2c). It remains stable again on this higher level until AD 1500 when a sudden distinct increasing trend lasting until today begins.

χ_{fd} is often used as a proxy for the relative contribution of surface erosion of clays and silts from well-developed low- to midaltitude soil profiles [Dearing *et al.*, 1996, 2001]. From AD 600 to 1500 χ_{fd} remains stable with values around $0.3 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. At AD 1500 the values suddenly increase to $1.2 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ (Figure 2d).

According to these results, the sequence can be divided into two zones (Figures 2c–2e) lasting from AD 600–1500 (93–39 cm) and AD 1500–2005 (39–0 cm).

4.2. Mineral Magnetic Properties of Selected Samples

Hysteresis loops are saturated in a 0.2 T field, indicating the dominance of low-coercivity ferrimagnetic minerals (Figures 3a and 3e). In addition, the shape of the hysteresis loops is consistent with the characteristics

Figure 4. Bilogarithmic plot of the quotients $\chi_{\text{ARM}}/\chi_{\text{fd}}$ and $\chi_{\text{ARM}}/\chi_{\text{if}}$ for samples from sediment core X06 from XLW (modified after Oldfield [2007]). The dashed circle indicates archaeological samples from the UK and Hungary and burnt topsoil samples from the Cotswolds region of England [Oldfield, 2007]. The shadow area indicates unburnt topsoil samples from the Cotswolds region of England [Oldfield, 2007] and Chinese paleosols reported by Chen et al. [1995] and Zheng et al. [1991].

of the samples (Figures 3d and 3h), probably due to fine grained particles or oxidization of magnetite [Smirnov, 2006].

4.3. Bi-Logarithmic Plot of $\chi_{\text{ARM}}/\chi_{\text{fd}}$ Versus $\chi_{\text{ARM}}/\chi_{\text{if}}$

Oldfield and Yu [1994] proposed that a bi-logarithmic plot of $\chi_{\text{ARM}}/\chi_{\text{fd}}$ versus $\chi_{\text{ARM}}/\chi_{\text{if}}$ can be used to distinguish the sources of magnetic minerals in sediments effectively, e.g., samples rich in biogenic magnetite (magnetosomes) and those rich in ferromagnetic minerals derived from eroded soils [Oldfield, 2013; Oldfield and Crowther, 2007]. Magnetic properties of the upper part of the sediments from XLW match well with unburnt topsoil samples from the Cotswolds region in England [Oldfield and Crowther, 2007] and Chinese paleosols reported by Chen et al. [1995] and Zheng et al. [1991] (Figure 4). Between AD 600 and 1500 only one data point is comparable to the above mentioned samples (Figure 4). This occurs at AD 630.

5. Discussion

The enhancement of χ_{if} and χ_{fd} since AD 1500 is probably caused by an increase in the concentration of SP particles. These fine-grained magnetic particles are often related to soils, in which ultra-fine SP and SD particles can be formed by pedogenesis [Liu et al., 2005; Zhou et al., 1990]. A strong correlation of $R^2 = 0.99$ with a similar slope can be observed between χ_{fd} and χ_{if} from XLW sediments and a soil profile nearby (Figures 1 and 5d). This suggests that the high χ_{fd} in the sediments of Lake XLW can be attributed to pedogenic soil. The pedogenetic soil components can be transported either fluvially or by aeolian processes into the lake. The study area is located in the pathway of dust storms [Qiu et al., 2001] and due to their small catchment area and closed morphology without rivers maar lakes act as “natural sediment traps” [Chu et al., 2009; Zolitschka et al., 2015]. The catchment is covered by dense forest, which limits minerogenic clastic input from local sources. Moreover, the area is supposed to be the birthplace of the Manchu people, the imperial family of the Qing dynasty (AD 1644–1911). Common people were not allowed to enter this area until 1970s. This means that the catchment was not exposed to human activity during this time [Chen, 2012]. Therefore, Chu et al. [2009] already assumed that the trend of increasing grain size in XLW sediments during the last 300 years can be related to an enhanced aeolian input of local origin.

Catchment materials may contain coarse particles, e.g., evident by a weak correlation between precipitation proxy $\delta^{13}\text{C}_{27-31}$ and χ_{if} from ~AD 1600 to AD 2000 (Figure 5a). However, these coarse-grained particles do

of single domain (SD) particles [Liu et al., 2012]. The FORC diagrams for the two representative samples are consistent with the horizontal distribution to 60 mT and peaks around 9 mT. The vertical distribution is less than 5 mT, demonstrating a relatively weak magnetic interaction. Some closed circles-like features indicate the existence of single domain (SD) particles and a few pseudo-single domain (PSD) particles (Figures 3b and 3f).

The χ – T curves (Figures 3c and 3g) show a relatively stable susceptibility with increasing temperature up to 420°C, followed by a significant rise at around 460°C. This may reflect the conversion of weakly magnetic paramagnetic minerals (e.g., iron silicates or clay minerals) into strongly magnetic ferrimagnetic minerals during heating [Liu et al., 2005]. Magnetization gradually declines from 520°C and approaches zero at 580°C, the Curie point of magnetite. Nevertheless, no visible Verwey transition can be detected at 120 K in the low temperature ZFC curves

Figure 5. Correlations between (a) χ_{lf} and $\delta^{13}\text{C}_{27-31}$, (b) M_z and $\delta^{13}\text{C}_{27-31}$, (c) χ_{fd} and $\delta^{13}\text{C}_{27-31}$ of XLW sediments, and (d) χ_{lf} and χ_{fd} of XLW sediments and the soil profile.

not contribute to the χ_{fd} signal because they are insensitive to the frequency-dependent measurements [Liu *et al.*, 2012]. No significant relationship is observed between χ_{fd} and temperature or rainfall proxies in the sediment record from XLW (Figures 2a, 2b, 2d, and 5c). Thus, the increase in χ_{fd} should not be related to changes in paleoclimatic conditions, but is assumed to be caused by an increasing influx of soil into the lake caused by increasing erosion due to human activities. Such a pattern was also reported from other regions of China. For example, recent sediments from the Yangtze delta in Eastern China are characterized by high values of both χ_{fd} and $\chi_{fd}\%$ carried by soil-derived SP minerals [Wang *et al.*, 2011]. Dearing *et al.* [2015] investigated the magnetic properties of Lake Erhai sediments in Yunnan, China. They observed that peak levels of disturbed land pollen taxa, topsoil, and gully erosion, defined by both χ_{lf} and χ_{fd} , are related to the documented environmental crisis in the late Ming and Qing dynasties (AD 1644–1911).

Evidence from lake sediments can be combined with historical records to produce an integrated record of the impact of human activity over time [Dearing *et al.*, 2015]. Previous studies have shown that human activities significantly changed the natural landscape of Northeastern China by land cultivation especially during the past 300 years [Ye *et al.*, 2009; Zhang *et al.*, 2011]. Major areas of Eastern Asia were converted from natural vegetation to anthropogenic cropland since the AD 1700 [Goldewijk *et al.*, 2011]. Since AD 1658, the Qing government issued “the order to encourage farming in East River Liao” to attract mainland people to migrate to Northeastern China [Chen, 2012]. Thus, more arable farmland in Northeastern China was needed.

Consequently, exploitation of remote mountain areas and development of dry farming in mountainous region should have caused intense soil erosion in Northeastern China, which is recorded by high χ_{lf} and χ_{fd} values since AD 1600 (Figure 2). Prior to AD 1600, both χ_{lf} and χ_{fd} already started to increase since AD 1500. This indicates that the natural land in this region could have already been substantially altered by human activity since AD 1500, although historical documents attest that the increase in the population occurred about two hundreds later at AD 1700 (Figure 2f) [Chen, 1997].

6. Conclusion

Detailed rock magnetic analyses indicate that increasing SP particles in sediments from XLW since AD 1500 can be attributed to an increasing influx of soil, which is related to enhanced human activities and consistent with Chinese population dynamics. This shifts the previously reported timing of significant human activities in Northeastern China from AD 1700 to AD 1500. Chinese population dynamics have a positive but nonlinear relation with the influx of soil into XLW.

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