ARTICLE IN PRESS

Quaternary International xxx (2015) 1–8

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Post-depositional forcing of magnetic susceptibility variations at Kurtak section, Siberia

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A R T I C L E I N F O

Article history:
Available online xxx

Keywords:
Magnetic susceptibility
Siberian loess
Ferruginous mottles
Paleosol
Post-depositional process
Rock-magnetism

A B S T R A C T

Magnetic susceptibility (MS) of aeolian deposits on the Chinese Loess Plateau is high in paleosol and low in loess. The MS of paleosols is mainly enhanced by ferromagnetic minerals formed during post-depositional soil development. In central Alaska, aeolian deposits, MS is high in loess and low in paleosol. The wind vigor model has been proposed to interpret such MS enhancement for the central Alaskan loess. This model suggests that the MS variations are determined by pre-depositional wind strength. The wind vigor model has been introduced to the Siberian Kurtak section where MS is also high in loess and low in paleosol. Additionally to the wind vigor model, low MS in paleosols could be triggered by post-depositional soil development and gleying when the pedogenesis and gleying transforms the ferromagnetic minerals to weak and non-magnetic minerals. In our study of the most continuous Kurtak section in western Siberia, we found that paleosols have substantially more ferruginous mottles due to water-saturated conditions. Magnetic analysis demonstrates that paleosols contain greater content of hard magnetic minerals compared to the loess. Temperature analysis of the MS in the ferruginous mottles shows that magnetic susceptibility increases 37 times after heating and cooling; half of the MS enhancements are contributed due to the heating in between 600 and 700 °C, being caused by the decomposition of non-magnetic chlorite. This suggests that pedogenesis and gleying at the Kurtak section produces weak and non-magnetic minerals in water-saturated anaerobic conditions, which deplete the MS in paleosols after deposition of loess.

1. Introduction

Studies of the widespread loess in north and northwest China have contributed significantly to our understanding of the paleoclimate changes (Heller and Tungsheng, 1984, 1986; Liu and Ding, 1998; Ding et al., 2002). Magnetic susceptibility has become a leading parameter to analyse paleoclimate records in loess sequences. Magnetic susceptibility of loess and paleosol sequences on the Chinese Loess Plateau increases due to stronger pedogenic development and correlates with the marine isotope curve (Heller and Tungsheng, 1984, 1986; Kukla et al., 1988).

For the Chinese loess, the mechanism of MS enhancement in paleosol has been well explained (Zhou et al., 1990; Heller et al., 1991; Liu et al., 2005). During glacial periods, wind steadily brings aeolian particles, which builds up the loess deposits. During interglacial periods, the temperature and precipitation strengthen the soil development and leads to additional production of ultrafine superparamagnetic (SP) and single domain (SD) ferromagnetic minerals (mainly magnetite and maghemite) (Zhou et al., 1990; Liu et al., 2005). Such in-situ new-formed fine ferromagnetic particles greatly boost the MS value in Chinese loess.

However, MS is not always higher in paleosols. For example, in central Alaska MS is higher in loess and lower in paleosol. Begét and Hawkins (1989) and Begét et al. (1990) demonstrated that aeolian dust from the neighboring basalt volcanoes carries more ferromagnetic particles, thus creating a stronger MS signal. Stronger winds during glacial intervals bring larger magnetic grains to the

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http://dx.doi.org/10.1016/j.quaint.2015.09.092
1040-6182/

Please cite this article in press as: Chen, J., et al., Post-depositional forcing of magnetic susceptibility variations at Kurtak section, Siberia, Quaternary International (2015), http://dx.doi.org/10.1016/j.quaint.2015.09.092

deposition sites. Interglacial soil development processes dilute the original signal by adding organic material during the pedogenesis. Relatively weaker winds bring smaller amounts of magnetic minerals to the deposition site; this depositional model was called the wind-vigor model (Evans and Heller, 2003). This model emphasizes the effect of MS enhancement during the depositional process and works well in Alaska and some arid areas with poor soil development (Sun and Liu, 2000).

The wind vigor model has initially been applied to Siberian sections, especially at Kurtak (Chlachula et al., 1998; Matasova et al., 2001; Evans et al., 2003; Zhu et al., 2003). However, Zhu et al. (2003) reported detectable goethite in the paleosols and proposed that the climate at Kurtak favored gleying of soils during interstadial and interglacial periods, leading to degradation and the destruction of magnetite and maghemite grains, but to the formation of weakly magnetic oxyhydroxides. Matasova et al. (2003) found that the paleosol had relatively high content of antiferromagnetic minerals, which was probably linked to pedogenic processes. Frequency dependent magnetic susceptibility (FD) related to the formation of new pedogenic ferromagnetic minerals is higher in paleosols than in loess (Chlachula et al., 1998; Kravchinsky et al., 2008).

Kravchinsky et al. (2008) demonstrated that MS variations in different west Siberian loess sections cannot be explained by this model exclusively and suggested that post-depositional processes took critical roles in post-depositional modifications of the MS signal. They assumed that gleying, acidification and podzolisation may cause MS to decrease by destroying original magnetic minerals and/or by limiting the formation of secondary ferromagnetic minerals. Based on detailed rock magnetism research, Liu et al. (1999, 2008) inferred that the extreme moist and cold condition, during interglacial periods in Siberia and central Alaska, tended to shape a reducing environment, which led to the formation of weakly magnetic iron oxyhydroxides and sulfides. Reduction process of ferromagnetic minerals to weakly magnetic iron oxyhydroxides and sulfides can effectively deplete the MS value.

Ferruginous mottles are widespread across the Kurtak section. The mottles are typical for paleosols and are scattered in loess. The mottles are typically a product of alternating oxidation and reduction conditions during the soil formation associated with pedogenesis and gleying under extremely environment (Chlachula, 2003). Here we analyze the magnetic properties of the ferruginous mottles to explore the role of pedogenesis and gleying on the transformation of magnetic minerals in order to decipher the mechanism of MS depletion after the formation of the Kurtak loess section.

2. Regional setting

The thickness ranges from a few meters to more than 100 m, while ages range more than 800 ka at an area of 7000 km^2; Siberian loess is distributed widely from Ob to Angara River basins (50°–66°N, 66°–97°E) in the southern central Siberia (Fig. 1(a)). Ice-sheet marginal areas, large alluvial flood plains, and margins of lacustrine basins are important sources of aeolian silts. Loess layers of Siberia correspond to relatively cold climate stages as evidenced by the correlation to the marine isotope curve (Zykina and Zykin, 2003). Paleosols have formed during relatively warm interglacial stages and interstadials of the Quaternary. These loess–paleosol sequences have provided an excellent record of the Pleistocene climate variations (Chlachula et al., 1998; Arkhipov et al., 2000).

The Kurtak area is one of the best-preserved belts of the Quaternary loess sections in Siberia. The typical present day vegetation cover is grassland and forest-steppe. Today's climate is strongly continental with long, cold and dry winters and warm to hot summers. There is little snow cover in winter, and the mean temperature is about 0.5–2 °C, while mean annual precipitation is 467 mm and mean annual humidity is 68%. The Kurtak section is located in the upper Yenisey River valley on the western side of Krasnoyarsk reservoir with subaerial thickness of about 30 m. Fig. 1(b) shows the Kurtak section; the section was dated by Zander et al. (2003). The stratigraphy was developed in Chlachula (2003) and Kravchinsky et al. (2008). The upmost soil unit corresponds to the Marine Isotope Stage MIS 1 and is the modern tundra-steppe soil rich in organic matter. MIS 2 and MIS 4 are massive sand units with little ferruginous mottles (Fig. 1(c)), while the intercalated MIS 3 is a clay chernozem type of paleosol with a lot of ferruginous mottles (Fig. 1(d)). The last interglacial pedocomplex MIS 5 (Fig. 1(e)) mainly consists of dark brown steppe chernozems mixed with a reddish brown coloured (ferruginous) stripe and intercalated by an aeolian loess unit. MIS 6 mainly comprises fine sand and MIS 7 is characterized by chernozem. Ferruginous mottles are distributed all over the section, also noted by Chlachula (2003), but there are more ferruginous mottles in the paleosols than the loess (Fig. 1). Ferruginous mottles at the Kurtak section exhibit intensive chemical/biochemical processes indicating post pedogenesis and gleying processes.

3. Material and methods

Loess and paleosol samples were collected at 10 cm intervals throughout the entire section. Low-field volume specific magnetic susceptibility was measured using a MS-2B Bartington Instruments susceptibility meter with low frequency at 470 Hz and high frequency at 4700 Hz. Grain size was analysed by a computer-operated PRO-700 SK Laser Micron Sizer. Saturation isothermal remanent magnetization (SIRM) was created in a direct magnetic field up to 1.4 T, using a 5-P electric magnet (Pilot Plant of the Siberian Branch of the RAS, Novosibirsk). Subsequently, the SIRM at 1.4 T was demagnetized in backfield 0.3 T to obtain $IRM_{-0.3T}$ for calculating HIRM and S-ratio. Magnetic hysteresis was measured with the MicroMag alternating gradient magnetometer (Model 2900, Princeton Measurements Corp.) with maximum applied field H_{max} = 1.5 T. Coercivity of remanence (B_{cr}) and mass-specific paramagnetic susceptibility (χ_{par}) were derived from magnetic hysteresis. Temperature-dependent susceptibility (heating up to 700 °C) was measured in an argon atmosphere with the furnace-equipped KLY-3 Kappabridge (Agico Ltd, Brno). The rock-magnetic and grain size measurements were conducted by G.G. Matasova from Novosibirsk (Siberian Branch of Russian Academy of Sciences). Stepwise temperature-dependent susceptibilities (χ-T) for the ferruginous mottles were measured in an argon atmosphere at the Key Laboratory of Western China's Environmental Systems, Lanzhou University. X-ray diffraction (XRD) analysis of the unheated and heated samples were carried out using a XPERT-PRO X-ray diffractometer at the Lanzhou University with the following parameters: Cu–K α/40 kV/40 mA, scan axis ranges from 5 to 75, divergence slit fixed at 0.76 mm, scan step size of 0.016711, continuous scan mode, time per step of 29.84 ms.

4. Results

4.1. Grain size and rock-magnetic properties under room temperature

Fig. 2(a) and (b) show the variations of MS and the coarse quartz grain size component (>40 μm) of the Kurtak section. The coarse quartz grain size component is an indicator of wind strength; presence of the coarser fraction indicates stronger winds which characterize cold and dry glacial intervals with weak soil