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Isolation of the syndepositional magnetic susceptibility signals from loessic paleosols of China

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Abstract

Bulk magnetic susceptibility (MS) has been widely used to differentiate the loess and soil units, and acts as a useful proxy of the intensity of summer monsoon to reconstruct the paleoclimate on the Chinese Loess Plateau. Since soil development occurs not only at the actual ground surface but also to a greater depth, bulk MS is overprinted by the post-depositional pedogenesis and can only be regarded as representative of a time period, rather than a specific point in time. Therefore, the bulk MS record, as a naturally smoothed curve, can illustrate the low-frequency Milankovitch cycles, but may be unable to adequately resolve high-frequency sub-orbital climatic changes.

Based on the pedosedimentary processes of soil formation, the Magnetic Susceptibility Variation (MSV) model is proposed to isolate the syndepositional enhancements of MS that may be directly linked to the climatic conditions of dust deposition. After an indirect test of the concept underlying the MSV model, using an atmospheric methane data set from Taylor Dome, Antarctica, we further verify the model directly from a loessic paleosol by the tentative correlation between the MSV record of Chinese loess at Luochuan profile and $\delta^{18}O$ of the NGRIP ice core within the last interglacial period. Our results show that MSV model may improve our understanding of widely used MS proxy itself, and climate variation within the interglacial time periods.

Keywords: Magnetic Susceptibility Variation (MSV); Syndepositional pedogenesis; Loessic paleosol; Last interglacial; Chinese Loess Plateau

1. Introduction

Our interests in the magnetism of the Chinese loess/paleosol sequence were sparked by the finding of high Magnetic Susceptibility (MS) values in paleosols formed under interglacial conditions and low MS values in loess units, and also by close correspondence between MS changes of Chinese loess and deep-sea oxygen isotope records (Heller and Liu, 1984; Liu et al., 1985; Kukla et al., 1988; Kukla and An, 1989; An et al., 1991; Verosub et al., 1993; Beer et al., 1993; Hunt et al., 1995; An, 2000; Porter, 2001). Origin of the MS signal, however, has been actively debated, and several contrasting hypotheses have been proposed. Despite the 'dilution hypothesis' proposed by Kukla et al. (1988), the prevailing view is that pedogenic processes, mainly controlled by precipitation and temperature, are responsible for the enhanced susceptibility signals in central China (Zhou et al., 1990; Heller et al., 1991; Verosub et al., 1993; Beer et al., 1993; Meng et al., 1997). Maher and colleagues (Maher and Taylor, 1988; Maher and Thompson, 1991; Maher et al., 1994a,b) attributed the MS signals to in situ production and concentration of the untrafine-grained magnetic mineral as a result of pedogenic activity. Liu et al. (1995) carried out a spatial analysis of the modern soils, suggesting a strong correlation between the superparamagmetic component and present precipitation. However, it is unclear whether time or climate is mainly responsible for the enhancement of MS. Singer et al. (1992) hypothesized that MS increases linearly with time on the basis of chronosequence studies of the California soils. Vidic et al. (2004) argue that climatic conditions are not the sole factor for the enhancement of MS, and the duration of pedogenesis also plays an important role on it.

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Anderson and Hallet (1996) incorporated dust deposition, pedogenic development and chemical compaction of soils in a numerical model, enabling them to explore quantitatively the role of the dust accumulation rate and pedogenesis in generating MS profiles. Recently, Porter et al. (2001) extended this idea and tried to isolate the dilution effect and the pedogenic effect by studying the near-surface MS of 80 sites throughout the Loess Plateau. Their model suggested that 84% of loess MS variance is dictated by the dilution effect, and 10–11% is associated with climatic factors, primarily precipitation.

In using a paleoclimatic proxy, both the reliability of the link between the proxy and climate, and the resolution of the proxy record are important. For the Chinese loess/paleosol sequence of the central Loess Plateau, even in recent interglacial periods, the average dust accumulation rate still amounted to about 4 cm/ka, so this geological carrier may register the climatic variation with the resolution of $\sim$1 ka. In terms of understanding of the significance of MS, many researchers have focused on the physical and mineralogical aspects of MS. However, less attention has been paid to soil forming processes and their effects on MS enhancement.

Here, we proposed a Magnetic Susceptibility Variation (MSV) model, based on the pedosedimentary processes that produce paleosols in the loess sequence, to isolate the syndepositional MS signal that can be directly linked to the climatic conditions when dust was deposited. Besides the mathematical deduction involved in the MSV model, we indirectly test its underlying concept by using it to extract much of the original high-resolution record of the atmospheric methane in an ice core from Antarctica, after the ice-core record is artificially smoothed. The MSV model is further tested by correlation between the MSV record of Chinese loess at the Luochuan profile and $\delta^{18}O$ of the NGRIP ice core (North Greenland Ice Core Project members, 2004).

2. Magnetic susceptibility variation (MSV) model

MS signal consists of two components: (1) the lithogenic component, dependent on the properties of the original dust, which is responsible for most of MS signal in loess; (2) the pedogenic components, dependent mostly on climatic conditions (precipitation and the temperature) controlled by the summer monsoon in the Loess Plateau (Zhou et al., 1990; Fine et al., 1995; Mishima et al., 2001), which is responsible for most of the MS signal in loessic paleosols. Vidic et al. (2000) have stated that reconstruction of paleoclimate based on total MS would be in error because total MS contains lithogenic susceptibility. Furthermore, because dust deposition continues as paleosols develop downward, the pedogenically-enhanced component of MS signals itself can also be separated into two parts: (2a) syndepositional enhancement acquired during deposition of a particular interval within the loess/paleosol sequence; and (2b) post-depositional enhancement acquired while that interval remains shallow enough to the ground surface to be affected by pedogenesis. The post-depositional effect has been studied by Pye (1995); Kemp (2001) for the pedogenic modification of loess. Syndepositional pedogenesis is overprinted by post-depositional alteration, both for aggrading accumulative soils and for soils that form downward from a stable land surface; this occurs over a depth ranging from tens of centimeter to several meters, depending on the regional climate. Therefore, the bulk MS record, as the result of naturally smoothing by post-depositional pedogenesis, can record climatic change at low-frequency Milankovitch cycles, but may not effectively display high-frequency climatic variation. The model proposed here extracts some of the original high-frequency variation removed in the smoothing caused by post-depositional pedogenesis and the lithogenic component of the original dust.

In presenting the MSV model, we assumed the loess/paleosol sequence to be consist of thin depositional layers. As mentioned above, the MS signal of each thin layer contains two parts: (1) the sedimentary dust component (MSD); and (2) the pedogenesis component (MSP):

$$\begin{aligned} \mathrm{MS}(n) &= \mathrm{MSD}(n) + \mathrm{MSP}(n); \\ \mathrm{MS}(n-1) &= \mathrm{MSD}(n-1) + \mathrm{MSP}(n-1) \end{aligned} \tag{1}$$

where $n-1$ represents the layer immediately above the layer n. Within a relatively uniform period such as the last interglacial, we assume variation of the parent material is negligible, so MSD(n) of every layer is equal, hence, the variation (MSV) of the top layer and the adjacent layer above is:

$$\Delta \mathrm{MS}(n) = \mathrm{MS}(n) - \mathrm{MS}(n-1) \tag{2}$$

$$\Delta \mathrm{MS}(n) = (\mathrm{MSD}(n) + \mathrm{MSP}(n)) - (\mathrm{MSD}(n-1) + \mathrm{MSP}(n-1)) \tag{3}$$

$$\Delta \mathrm{MS}(n) = \mathrm{MSP}(n) - \mathrm{MSP}(n-1) \tag{4}$$

Another important concept built into this model is that pedogenesis occurs not only at the surface layer in the contact with the atmosphere, but also a greater depths until the layer is below the depth of effective pedogenic processes. Because pedogenic component of MS signals of a single layer can also be separated into two parts: (2a) syndepositional enhancement, and (2b) post-depositional enhancement as later $n-1$ loess-layers deposited, which still affected layer(n). Therefore, MSP(n) and MSP($n-1$) can be calculated as follows:

$$\begin{aligned} \mathrm{MSP}(n) = {} & F_n^n(T_n, P_n) + F_{n-1}^n(T_{n-1}, P_{n-1}) \\ & + F_{n-2}^n(T_{n-2}, P_{n-2}) + \cdots + F_1^n(T_1, P_1) \\ & + F_0^n(T_0, P_0) \end{aligned} \tag{5}$$