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Characterizing the superparamagnetic grain distribution of Chinese red-clay sequences by thermal fluctuation tomography

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ABSTRACT

Although magnetic susceptibility (χ) is a widely accepted East Asian summer monsoon (EASM) intensity proxy for Quaternary loess, debates exist about whether χ can be used to indicate EASM intensity for the red-clay sequence. In order to use χ of the red-clay sediments to indicate EASM intensity, χ should have the same sort of enhancement mechanisms as in Quaternary loess. However, this similarity has not been rigorously demonstrated. Previous estimates of magnetic grain size distribution of Chinese loess and red-clay are based on out-of-phase magnetic susceptibility inversion technique. This technique assumes that the coercivity of pedogenic magnetic grains is independent of temperature, and at any temperature, only a single grain size contributes to frequency-dependent or quadrature susceptibility, rather than a distribution of sizes. Thermal fluctuation tomography is a recently developed more rigorous inversion technique for characterizing the grain-size distribution of superparamagnetic (SP) and single domain grains with fewer assumptions. Here we apply this technique to the Chinese red-clay sequence of the Chaona section, central Chinese Loess Plateau, and the overlying loess–paleosol sequence to better characterize the size distribution of SP grains of the Chinese red-clay sequence. We found that SP grain-size distributions of both paleosol and red-clay from the Chaona section are similar. The results reinforce a previous conclusion supporting the idea that magnetic susceptibility (χ) can be used to indicate the intensity of the EASM in the red-clay sequence.

1. Introduction

Much progress has been made recently in understanding orbital-scale and tectonic-scale forcing mechanisms of climate on the Chinese Loess Plateau (CLP) for the last 6 Myr (Nie et al., 2008a,b,c; Sun et al., 2010; Nie, 2011). These inferences about climatic forcing mechanisms are largely based on the assumption that magnetic susceptibility (χ or χ_{lf}) of pre-Quaternary deposited loess (i.e., red-clay) on the CLP is a valid proxy for the intensity of the East Asian summer monsoon (EASM). Although χ is a widely accepted EASM intensity proxy for Quaternary loess, debates exist about whether χ can be used to indicate EASM intensity for the red-clay sequence (An et al., 2001; Ding et al., 2001).

It has long been accepted that enhancement of χ in Quaternary loess is caused by the production of SP grains associated with pedogenesis (Zhou et al., 1990; Maher et al., 1994; Heller and Evans, 1995). In order to use χ of the red-clay sediments to indicate EASM intensity, χ should have the same sort of enhancement mechanisms as in Quaternary loess. However, this similarity has not been rigorously demonstrated. Previous estimates of magnetic grain-size distribution of Chinese loess and red-clay are based on out-of-phase magnetic susceptibility versus temperature data, using the assumption that the coercivity of pedogenic magnetic grains is independent of temperature, and thus has important caveats (Liu et al., 2007; Nie et al., 2008b). In this paper, we apply the recently developed thermal fluctuation tomography (TFT) (Jackson et al., 2006) method to more rigorously map the grain size distribution of pedogenic superparamagnetic grains in representative loess and red-clay samples.

2. Samples and methods

We quantify the joint distribution of grain volume (V) and microcoercivity (H_k), $f(V,H_k)$ of ultrafine ferrimagnetic particles from 1 paleosol and 3 red clay samples from the Chaona section (Fig. 1) using the TFT technique (Jackson et al., 2006). Back-field remanent magnetization curves were measured using applied fields from 0 up to 300 mT with a 5 mT step, over a temperature range of between 10 K and 300 K at 10 K interval, using a Princeton Measurements MicroMag vibrating-sample magnetometer (VSM). Following Dunlop (1965), using the thermal activation theory of Néel (1949)

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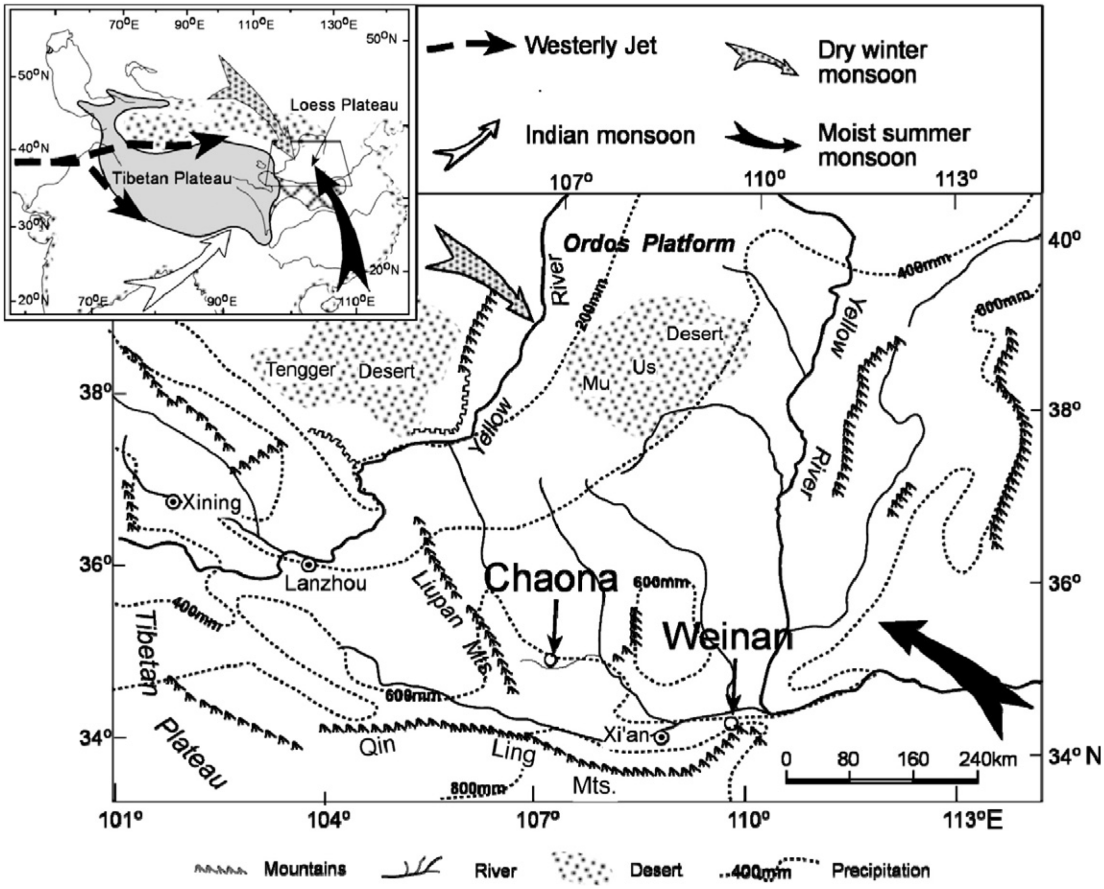

Fig. 1. Schematic map showing the physical geography of the CLP and the location of the Chaona and the Weinan sampling sites. The inset illustrates the location of the CLP in relation to Tibet and the modern Asian atmospheric circulation pattern.
Revised from Fig. 1 in Song et al. (2007).

the temperature-dependent switching-field distributions are mapped into the joint distribution of particle size and microcoercivity, under the assumptions that the population of magnetic particles is mineralogically homogeneous, that the individual grains are uniformly magnetized and dominated by uniaxial shape anisotropy, and that moments reverse by coherent rotation (Jackson et al., 2006). An iterative algebraic reconstruction technique, similar to those used in seismic tomography, is used for the inverse model calculations (Jackson et al., 2006). Finally, we convert this joint distribution into a univariate grain size distribution by integrating $f(V,H_k)$ over the range of microcoercivity values.

3. Results

Figs. 2 and 3 show $f(V,H_k)$ and the univariate volume distribution of 1 paleosol sample and 3 red-clay samples from Chaona estimated using the TFT technique. For comparison, we also include the univariate volume distribution for the paleosol sample from Weinan used in Jackson et al. (2006) (Fig. 3). It is clear that all Chaona samples have similar $f(V,H_k)$ and volume distributions. A comparison with the Weinan paleosol sample suggests that the volume distribution of the Weinan sample is slightly narrower than the Chaona samples. Fig. 4 shows a comparison between the univariate grain size distribution of 1 paleosol and 1 red clay sample from Chaona based on the TFT technique and the AC magnetic susceptibility technique (Nie et al., 2008b), respectively. The volume distribution was converted into grain size distribution by assuming spherical grains. Clearly, the different techniques generate different distribution curves.

4. Discussion and conclusions

The magnetic grain size distribution reconstruction using thermal fluctuation tomography and AC susceptibility for the same sample is not consistent (Fig. 4). The possible reasons are threefold. First, the AC susceptibility inversion method that we have used (Liu et al., 2005; Nie et al., 2008b) is a very simplified treatment. It assumes a value for the coercivity of pedogenic maghemite and treat it as independent of T. Moreover, it effectively assumes that at any temperature, only a single grain size contributes to frequency-dependent or quadrature susceptibility, rather than a distribution of sizes. TFT is a more rigorous inversion method, which relies on more detailed measurement data and fewer assumptions. Second, magnetostatic interactions might affect the AC susceptibility results much more significantly than those from TFT. Numerous studies have shown that interparticle interactions have strong effects on the susceptibility behavior of SP populations, and properly accounting for these effects in the inverse calculation is extremely complex (Muxworthy, 2001; Shcherbakov and Fabian, 2005; Egli, 2009). The neglect of interaction effects in our simplified inversion may therefore significantly skew the calculated size distribution. In contrast, TFT analysis of strongly-interacting ferrofluids yielded accurate estimates of particle sizes and shapes, whereas forward (noninteracting) models of $\chi(f,T)$ for the known sizes disagreed substantially with measured $\chi(f,T)$ (Jackson et al., 2006). Finally, antiferromagnetic minerals might affect the results obtained using TFT more significantly than those obtained using AC susceptibility, since such minerals would be expected to contribute proportionally far more to remanence than to susceptibility. Because of these differences between these two methods, it is reasonable to see the different shapes of the grain size curves in Fig. 4.