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Soil moisture balance and magnetic enhancement in loess–paleosol sequences from the Tibetan Plateau and Chinese Loess Plateau

Pengxiang Hu [a,b], Qingsong Liu [a,*], David Heslop [c], Andrew P. Roberts [c], Chunsheng Jin [a]

[a] Division of Tethys Research Center, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, People's Republic of China
[b] University of the Chinese Academy of Sciences, Beijing 100049, People's Republic of China
[c] Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia

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ABSTRACT

We present a first combined environmental magnetic and geochemical investigation of a loess–paleosol sequence (<55 ka) from the Chuanxi Plateau on the eastern margin of the Tibetan Plateau. Detailed comparison between the Ganzi section and the Luochuan section from the Chinese Loess Plateau (CLP) allows quantification of the effects of provenance and climate on pedogenic magnetic enhancement in Chinese loess. Rare earth element patterns and clay mineral compositions indicate that the Ganzi loess originates from the interior of the Tibetan Plateau. The different Ganzi and CLP loess provenances add complexity to interpretation of magnetic parameters in terms of the concentration and grain size of eolian magnetic minerals. Enhanced paleosol magnetism via pedogenic formation of ferrimagnetic nanoparticles is observed in both sections, but weaker ferrimagnetic contributions, finer superparamagnetic (SP) particles and stronger chemical weathering are found in the Ganzi loess, which indicates the action of multiple pedogenic processes that are dominated by the combined effects of mean annual precipitation (MAP), potential evapotranspiration (PET), organic matter and aluminium content. Under relatively high MAP and low PET conditions, high soil moisture favours transformation of ferrimagnetic minerals to hematite, which results in a relatively higher concentration of hematite but weaker ferrimagnetism of Ganzi loess. Initial growth of superparamagnetic (SP) particles is also documented in the incipient loess at Ganzi, which directly reflects the dynamic formation of nano-sized pedogenic ferrimagnets. A humid pedogenic environment with more organic matter and higher Al content also helps to form finer SP particles. We therefore propose that soil water balance, rather than solely rainfall, dominates the type, concentration and grain size of secondary ferrimagnetic minerals produced by pedogenesis.

1. Introduction

Environmental magnetism is an interdisciplinary subject that involves a wide spectrum of geological and environmental problems (Dekkers, 1997; Q.S. Liu et al., 2012 and references therein; Oldfield, 1991; Thompson and Oldfield, 1986; Verosub and Roberts, 1995). Loess deposits provide semi-continuous records of terrestrial paleoclimate and are a key archive with which to reconstruct monsoon evolution, aridification history, and abrupt climate change using magnetic properties (An, 2000; Deng et al., 2006; Ji et al., 2004; Liu et al., 2007 and references therein). However, loess magnetism depends on different regional paleoenvironmental factors, which complicates magnetic interpretation. For instance, the magnetism of loess–paleosol sequences in Alaska and Siberia is explained by a wind-vigour model, whereby eolian iron oxide grains play a dominant role in controlling magnetic properties (Begét et al., 1990; Chlachula et al., 1998). In contrast, loess sequences in Eastern Asia and Europe contain magnetically enhanced paleosol layers that result from pedogenic formation of ultrafine superparamagnetic (SP) and single domain (SD) magnetite and/or maghemite grains (Boyle et al., 2010; Dearing et al., 1996; Liu et al., 2007; Zhou et al., 1990). Therefore, to understand the environmental magnetic signal carried by loess–paleosol sequences, two key problems must be addressed. First, magnetic minerals from different sources must be identified, characterized and quantified. Second, the identified minerals must be attributed to specific environmental processes.

Many studies have addressed the first problem through use of rock magnetic and mineralogical methods (Egli, 2004; Geiss and Zanner, 2006; Heslop et al., 2002; Heslop and Roberts, 2012a; Roberts et al., 2000, 2006). Hu et al. (2013) integrated dynamic

* Corresponding author at: Division of Tethys Research Center, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, People's Republic of China. Tel.: +86 10 82998365; fax: +86 10 62010846.
E-mail address: liux0272@yahoo.com (Q. Liu).

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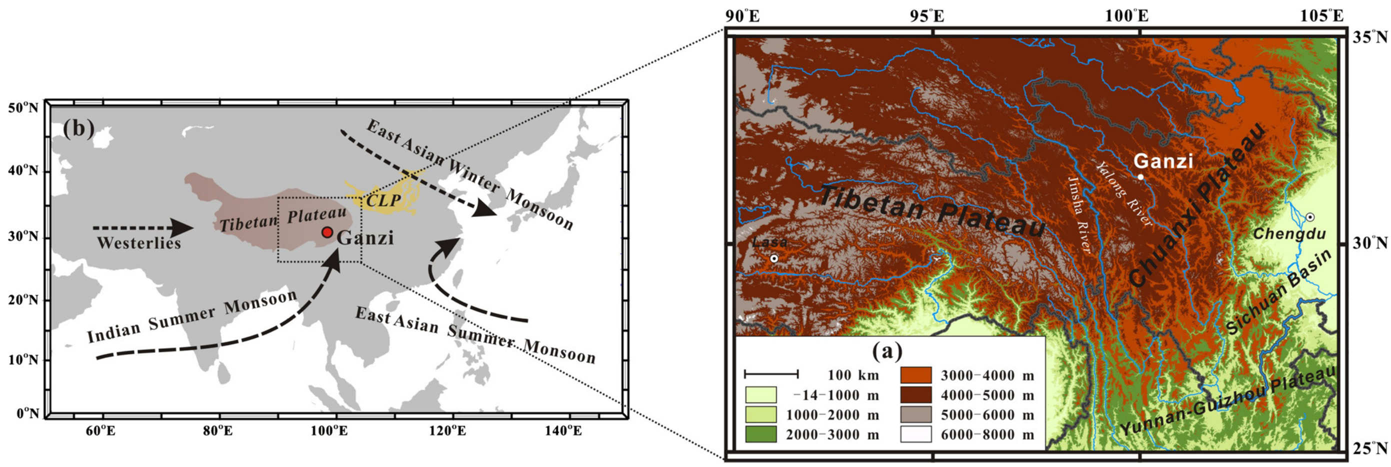

Fig. 1. (a) Map with regional elevations and location of the Ganzi section and adjacent areas. Elevation data are from the International Scientific & Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences. (b) Schematic map of the studied area with monsoon illustration. The Ganzi area is mainly under the influence of the Indian monsoon flow from the Arabian Sea and Bay of Bengal in summer and westerlies during winter. In contrast, the East Asian Summer and Winter monsoon is the dominant atmospheric circulation system on the CLP.

dissolution, rock magnetic and diffuse reflectance spectrometer (DRS) techniques to separate and quantify lithogenic and pedogenic magnetic minerals in Chinese loess. The aim of this paper is to build on previous work to evaluate environmental factors that control the magnetic properties of loess–paleosol sequences. The influence of provenance factors on soil magnetism, such as Fe supply (Dearing et al., 1996; Maher, 1998), topography (Liu and Liu, 2014), and climatic factors, such as mean annual precipitation (MAP) and potential evapotranspiration (PET) (Balsam et al., 2011; Liu et al., 2013; Maher et al., 1994; Orgeira et al., 2011; Porter et al., 2001) have been investigated in modern soils. In well-studied parts of the Chinese Loess Plateau (CLP) loess–paleosol sequences (e.g. the Malan loess), which are developed on similar topography, provenance and climate have been shown to be the most important factors that control the magnetic signal (Evans and Heller, 2001; Liu et al., 2007). On this basis, comparative environmental magnetic studies on loess–paleosol sequences in different climate zones with different source areas are needed urgently.

Loess–paleosol sequences are widely distributed in China, which provides an opportunity for comparative studies. Environmental magnetic investigations have been performed widely on loess deposits from the CLP, but comparative studies outside the CLP are rare despite their potential to provide insights into relationships between magnetic properties, climate and source material variations (Y. Liu et al., 2012; Wei et al., 2013; Zan et al., 2010; Zhang et al., 2007). Continuous loess deposition also occurred over the Chuanxi Plateau, southeastern Tibetan Plateau (Fig. 1a). The climate of the Chuanxi Plateau is largely controlled by interactions among the Tibetan monsoon, Indian monsoon and westerlies (Chen et al., 2002; Pan and Wang, 1999), and the loess source area is potentially different from the CLP (Fang, 1994; Fang et al., 1996; Qiao et al., 2006; Wang et al., 2003). Therefore, the Chuanxi loess provides an opportunity to quantify the effects of source material and climate on pedogenic magnetic mineral formation. We present an integrated rock magnetic, geochemical and DRS investigation of a Chuanxi loess–paleosol sequence, which has been forming since ∼55 ka. By comparing the Chuanxi loess–paleosols to contemporaneous CLP deposits, we provide new lines of evidence concerning the dominant factors that influence the magnetism of loess–paleosol sequences.

2. Material and methods

2.1. Geographic setting and sampling

The Chuanxi Plateau is bordered by the Sichuan Basin to the east, the Jinsha River to the west and the Yunnan–Guizhou Plateaus to the south. Its elevation decreases from 4000–4500 m in the west to 3000–3500 m in the east (Fig. 1a). As a result of multiple Quaternary uplift episodes of the Tibetan Plateau, river terraces have formed by erosion. Loess deposits are widely and continuously distributed over higher river terraces. The Ganzi loess section (31°30.994′N, 99°58.590′E, 3455 m elevation) is located in the western Chuanxi Plateau (Fig. 1a). MAP in this area is 660 mm (30 yr average from 1971 to 2000). Most precipitation occurs in the summer (May to September), which accounts for ∼81% of the annual total. The mean annual temperature (30 yr average from 1971 to 2000) is 5.6 °C, with a maximum of 13.9 °C in July and a minimum of −4.4 °C in January. Today, the Ganzi section is under the influence of the Indian monsoon and westerlies in summer and winter, respectively (Fig. 1b).

The Ganzi section is located on the fifth terrace of the Yalong River (Fig. 1a). It has a thickness of 14.5 m and is composed of seven main units, which are described following the CLP convention: (1) a brown cultivated topsoil, which is excluded from this study; (2) modern loess – L0; (3) a Holocene paleosol – S0; (4) the last glacial Malan loess – L1, which in turn includes two loess sublayers (L1L1 and L1L2) and two weakly developed paleosols (L1S1 and L1S2). These layers are described in Table A.1. The section was sampled at 2-cm stratigraphic intervals for this study; 725 samples were collected. Five samples for optically stimulated luminescence (OSL) dating were taken by driving stainless steel tubes into the fresh outcrop at each stratigraphic boundary. Fine quartz particles were selected for OSL dating and were prepared following J.F. Liu et al. (2010). Measurements were performed using a Daybreak 1100 TL/OSL automatic measurement system in the Luminescence Dating Laboratory of the State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration. The five resulting OSL ages are shown in Fig. 2a, which demonstrate that the Ganzi section has been forming since the early part of marine isotope stage (MIS) 3 (dated at 55.2 ± 2.7 ka).

We compare the Ganzi loess that was deposited through the last glacial cycle (including S0, L1L1, L1S1, L1L2, L1S2) to contemporaneous material from the Luochuan section on the central CLP (Fig. 3). MAP at Luochuan is 511 mm (1971 to 2000), with summer