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Palaeoclimatic and hydrological environments inferred by moisture indexes from the S_4 palaeosol section in the Xi'an region, China

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ABSTRACT

We used indexes of soil moisture content to reconstruct water balance and vegetation type during the development of the palaeosol S_4 of the loess-palaeosol sequence in the Xi'an area of China. Goethite–Fe-Mn concretions were found within S_4 from field survey and laboratory analyses, and their presence is used as an indicator of soil moisture content and the depth distribution of groundwater. From a comparison of the goethite–Fe-Mn concretions, weathered-leached loess layer, and the vertical migration distance of $CaCO_3$ between various sections in the Xi'an region, we infer a subtropical climate with annual average temperature 15–16 °C and annual average precipitation of 900–1000 mm during the development of S_4. At that time, unlike today, the Qinling Mountains were not the boundary between subtropical and temperate climatic regions. Our results show that the depth distribution of soil gravitational water in the Xi'an region reached 3.3 m; the average soil moisture content within the 0–3.3 m depth range was ~25%, after water consumption by evapotranspiration; and the soil moisture content within the goethite–Fe-Mn concretion layer was close to saturation, at ~48%. Soil moisture was abundant and the water balance was positive and a large amount of moisture was supplied to the groundwater each year, which was conducive for the development of forest vegetation.

1. Introduction

Since 2.6 Ma, nearly 40 layers of loess (L) and 40 layers of red-brown palaeosol (S) have been developed in the Chinese Loess Plateau (Liu et al., 1985). In these loess and palaeosol layers, the fourth palaeosol layer (S_4) is well-developed and its pedogenic intensity is only second to the fifth palaeosol layer (S_5) with the greatest pedogenic intensity. Loess research has made a major contribution to our understanding of global environmental changes during the Quaternary (Liu et al., 1985; An et al., 1991; Hwang et al., 2014; Li et al., 2015; Schatz et al., 2015). For example, the outcrops of Quaternary loess strata in the Guanzhong Plain of the southern Loess Plateau in China are valuable archives for reconstructing Quaternary climate change (Zhao et al., 2012 ; Kang et al., 2013). Many previous studies have been conducted on loess profiles in the Guanzhong Plain, such as in Xi'an (Lin and Liu, 1992 ; Zhao et al., 2012), Weinan (Guo et al., 1998), and Baoji (Lü et al., 1996), and one of the major findings of these studies is that S_4 developed under a temperate semi-humid or semi-arid climate, with the dominant vegetation type of forest steppe (Lin and Liu, 1992; Cai et al., 2013), in an overall subtropical environment (Guo et al., 1998).

The development of S_4 is equivalent to Marine Isotope Stage (MIS) 11 (Liu, 1985; Ruddiman et al., 1989; Hao et al., 2012). S_4 is also well-developed in the Czech Republic (Kukla, 1977; Marković et al., 2015), Germany (Pécsi, 1987), the US (Kukla, 1987), Central Asia (Dodonov and Baiguzina, 1995), and New Zealand (Eden, 1989). Despite the large number of studies of loess-palaeosol sequences, few have focused on Fe-Mn concretions that are potentially useful indicators of soil moisture content and hydrological environment during palaeosol development. Moreover, few studies have been conducted on iron oxide minerals such as goethite in loess (Balsam et al., 2004; Liu et al., 2010; Yan et al., 2012), although the visible of layers of goethite, Fe-Mn concretions, and leached loess layers are undoubtedly sensitive indicators of palaeo-moisture content. In this study, we analyzed the relationships among goethite, Fe-Mn concretions, leached loess layers and $CaCO_3$ concretions at sites in the Xi'an region. Our aim was to infer the soil moisture content, distribution of gravitational water, and water circulation associated with the development of S_4. Our work on the weathered loess layer and depth migration of chemical components is a new approach for reconstructing climate and vegetation during the development of S_4.

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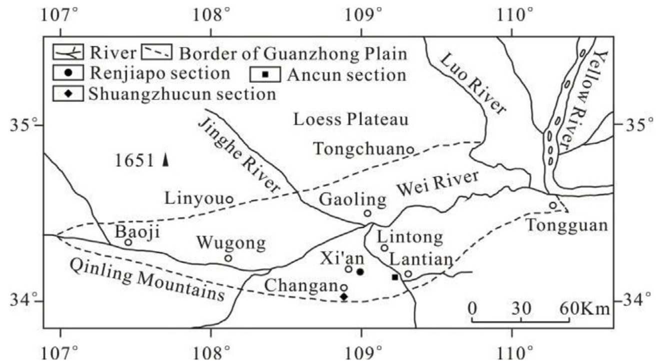

Fig. 1. Map of the geographical settings and study sites in the Xi'an region.

2. Study area and methods

Xi'an city is in the central Guanzhong Plain at 33°42′–34°44′N and 107°40′–109°49′E (Fig. 1). The Xi'an region is in a warm temperate zone and has a semi-humid monsoon climate, with an annual average temperature of 13.1 °C, an annual average precipitation of 603 mm, and four distinctive seasons. The modern vegetation is broadleaf deciduous forest, and the soil type is a drab soil. Loess deposits and loess landforms are well-developed in the Xi'an region. The Bailu Tableland and Shaoling Tableland, in the eastern and southern suburbs, are formed by loess. There is a complete sequence of Quaternary loess and palaeosols, with a thickness of ~120 m. The Ancun profile is at the easternmost end of the Bailu Tableland, ~5 km from the west of Lantian County (Fig. 1), and about 45 km from Xi'an City. The profile is near the Qinling Mountains, and the area has an annual average precipitation of ~700 mm. The Renjiapo profile is at the western end of the Bailu Tableland, in the eastern suburbs of Xi'an City, about 15 km from downtown Xi'an (Fig. 1). The Shuangzhu profile is at the northern end of Shaoling Tableland, in the southern suburbs of Xi'an City, ~2 km from the south of Chang'an County (Fig. 1).

The methods used in this study included field surveys and observations, electron microscopy, energy spectrum analysis, optical microscope observations, and X-ray diffraction analysis. $CaCO_3$ content within S_4 was analyzed at a 2-cm interval in the Renjiapo and Shuangzhu profiles, and every 25 cm in the Ancun profile; a total of 79 samples was obtained from the three profiles. One concretion sample and one goethite sample was collected every 3 cm in the Fe-Mn concretion layer, yielding 12 samples of each. Red Fe-Mn argillans samples and whole-rock samples were collected every 15 cm in the Bt layer in the three sections, yielding 24 samples of each type.

For electron microscopy and energy spectrum analysis, a sample with a diameter of ~5 mm and a thickness of ~2 mm was prepared, which was then gold sputtered. The error in the energy spectrum analysis was less than ~3%. For X-ray diffraction analysis, samples were ground into powder, and a sample with a diameter of less than 0.05 mm was obtained using a 0.05 mm-diameter copper sieve. The X-ray diffraction voltage was 40 kV and the current was 200 mA; the analytical error was about 1–5%, depending on the content of the mineral. Soil microstructures were observed with a light microscope, and the $CaCO_3$ content was determined using the gasometric method, with an error of < 0.26%. The electron microscopy observations and analyses were completed at Shaanxi Normal University, and the X-ray diffraction analysis was carried out at the Xi'an Institute of Geology and Mineral Resources.

3. Results

3.1. Stratigraphy of S_4 in the Xi'an region

Field observations revealed two types of illuvial layer in S_4. The first type (Fig. 2A) has the following layers, in order of increasing depth: (i) rufous argillic layer (Bt), with a thickness of about 1.4 m; (ii) weathered-leached loess layer (Bs) (Eswarean et al., 2002) containing red Fe-Mn argillans, with a thickness of about 1 m; (iii) weathered-leached loess layer (Cl) without iron cutans, with a thickness of ~0.6 m; (iv) $CaCO_3$ concretion illuvial layer (Ck), with a thickness of ~30 cm; (v) loess parent material (C, not represented in Fig. 2A), which is relatively unweathered. This type of illuvial layer within S_4 is not distributed at the bottom adjacent to the argillic layer, but in the loess parent material layer, ~2 m beneath the argillic layer. The distribution pattern of this type of illuvial layer is the most common pattern in the region, and is also characteristic of the leached soil (Xiong and Li, 1987; Zhu and He, 2001). In the second type of S_4 profile (Fig. 2B), the following layers are present: (i) the first layer is also the argillic layer (Bt), with a thickness of ~1.4 m; (ii) weathered-leached loess layer (Bs) containing Fe-Mn argillans, with a thickness of ~3.5 m; (iii) weathered-leached loess layer (Ce) containing combined goethite–Fe-Mn concretions, with a thickness of ~0.6 m; (iv) red-brown palaeosol (S_5, not represented in Fig. 2B). In this type of profile, the leached $CaCO_3$ is replaced by Fe-Mn argillans and Fe-Mn concretions. The migration of Fe and Mn oxides, and the formation of Fe-Mn concretions, represents the highest degree of leaching and they are prominent characteristics of the acid soil.

3.2. Weathered-leached loess layer and Fe-Mn argillans in S_4

Visual observations revealed that the weathered-leached loess layer (Bs layer and Cl layer in Fig. 2A), with a thickness of ~1.6 m, is universally developed within S_4 in the Xi'an region. It is the loess layer which was affected mainly by leaching by soil water from precipitation, and temperature-induced oxidation during the development of the overlying palaeosol. The loess layer has well-developed leached fissures, and a very low $CaCO_3$ content. The thickness of the weathered-leached loess layer (Bs layer in Fig. 2B) in the Ancun section in Lantian reaches 3.5 m. In the weathered-leached loess layer, the vertical

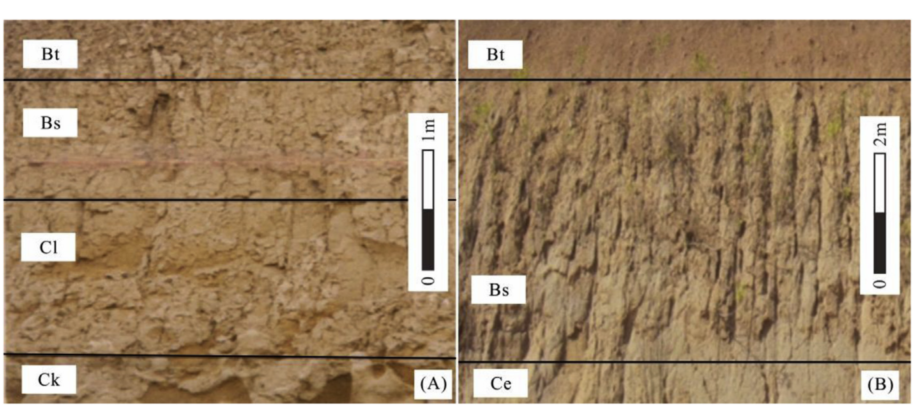

Fig. 2. Stratigraphic division of S_4 profiles in Shuangzhu (A) in the southern suburbs of Xi'an and in Ancun (B) in Lantian of Xi'an. Bt) argillic layer; Bs) weathered-leached loess layer containing red Fe-Mn argillans and leached fractures; Cl) weathered-leached loess layer without red iron cutans; Ck) $CaCO_3$ concretion illuvial layer; Ce) weathered-leached loess layer containing combined goethite–Fe-Mn concretions.

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