Quaternary Science Reviews 169 (2017) 312–329

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Tectonic uplift-influenced monsoonal changes promoted hominin occupation of the Luonan Basin: Insights from a loess-paleosol sequence, eastern Qinling Mountains, central China

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A R T I C L E I N F O

Article history:
Received 23 January 2017
Received in revised form
19 May 2017
Accepted 30 May 2017

Keywords:
Pedogenic weathering
Pleistocene
East Asian monsoon
Paleoclimatology
Sediment mineralogy
Rare earth elements

A B S T R A C T

Quaternary soil deposits from northern and southern China are distinctly different, reflecting variability of the East Asian monsoon north and south of the Qinling Mountains. Coeval sediments from the transitional climatic zone of central China, which are little studied to date, have the potential to improve our understanding of Quaternary monsoon changes and associated influences on hominin occupation of this region. Here, we investigate in detail a well-preserved and continuous Quaternary loess-paleosol sequence (Shangbaichuan) from the Luonan Basin, using a variety of weathering indices including major and trace element ratios, clay mineralogy, and Fe-oxide mineralogy. The whole-rock samples display similar rare earth element patterns characterized by upper continental crustal ratios: $(La/Yb)_N \approx 9.5$ and $Eu/Eu^* \approx 0.65$. Elemental data such as $(La/Yb)_N$, La/Th and Eu/Eu^* ratios show a high degree of homogeneity, suggesting that dust in the source region may have been thoroughly mixed and recycled, resulting in all samples having a uniform initial composition. Indices for pedogenic weathering such as Na/K, Ba/Sr, Rb/Sr, CIA, CIW, CPA, PIA, kaolinite/illite, (kaolinite + smectite)/illite, and hematite/(hematite + goethite) exhibit similar secular trends and reveal a four-stage accumulation history. The indices also indicate that the climate was warmer and wetter during the most recent interglacial stage, compared with coeval environments of the Chinese Loess Plateau. Secular changes in weathering intensity can be related to stepwise uplift of the Qinling Mountains and variation in East Asian monsoon intensity, both of which played significant roles in controlling climate evolution in the Luonan Basin. Furthermore, intensified aridity and winter monsoon strength in dust source areas, as evidenced by mineralogic and geochemical changes, may have been due to the mid-Pleistocene climate transition. Based on temporal correlation of warmer and wetter climatic conditions with more frequent hominin occupation, we infer that the paleoclimate in the eastern Qinling Mountains remained mild and favorable during glacial stages of the Late Quaternary, thus promoting early human settlement.

1. Introduction

The East Asian monsoon (EAM), which is an important component of the global climate system, is a major control on hydrological and environmental changes in East Asia (An, 2000; An et al., 2015). The EAM is characterized by long-term (~10^4–10^5 yr) alternations in dominance between the warm/humid summer

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http://dx.doi.org/10.1016/j.quascirev.2017.05.025
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monsoon and the cold/dry winter monsoon, which are coupled with variations in solar radiation and continental ice volume (An et al., 2001, 2015; Wang et al., 2005). The EAM circulation influences water supply and agricultural food production in East Asia, and can also create natural hazards such as flooding and drought, affecting 30% of the world's population (Sun et al., 2015). Because knowledge of monsoon variability during the geological past is essential to a better understanding of the present climate system and prediction of future climatic changes, interest in the history of the EAM has been increasing (e.g., Chen et al., 2006; Clift et al., 2014; An et al., 2015; Lu, 2015; Sun et al., 2011, 2015).

The climate evolution of northern and central China during the Quaternary has been largely controlled by variations in intensity of the East Asian summer monsoon (EASM) and East Asian winter monsoon (EAWM). In northern China, the Chinese Loess Plateau (CLP) contains abundant loess-paleosol sequences that represent valuable records of multi-cycle changes of continental climatic conditions (Kukla and An, 1989; Liu and Ding, 1998; Balsam et al., 2004; Torrent et al., 2007). In southern China, Quaternary red earth sediments are accretionary in nature, recording intense syndepositional weathering in a subtropical to tropical monsoonal climate (Qiao et al., 2011).

The relatively sharp transition between Quaternary sediment types in northern and southern China is due to the presence of the Qinling Mountain Belt (QMB) in central China (Fig. 1; Cai et al., 2010; Zhang et al., 2012). The QMB partially blocks the circulation of monsoon air and marks a significant climatic boundary: the northern and southern sides of the QMB are characterized by distinct climates and vegetation cover (Lu et al., 2007, 2011).

The Luonan Basin to the east of the QMB, which contains many surface and *in situ* lithic artifacts, is viewed as a vital region for understanding the history of hominin settlement in East Asia (Lu et al., 2007, 2011). This basin is also recognized by archaeologists as the transitional region between the northern China flake-core tool industries and the southern China pebble-core tool industries (Wang, 2005; Sun et al., 2013, 2014).

Studies of sediment magnetic stratigraphy and optically stimulated luminescence (OSL) have shown that early humans occupied the Luonan Basin intermittently during the early to middle Pleistocene (Lu et al., 2007, 2011). Existing research has proposed that the Luonan Basin was a suitable place for hominin settlement based on investigations of environmental magnetism (Wang, 2005; Wang-X et al., 2016). Nevertheless, the stimulus for multiple stages of hominin occupation of the Luonan Basin during the Late Quaternary remains unclear. Also unresolved is the driving force of monsoonal changes in the Luonan Basin, which is important for an improved understanding of the EAM generally.

Several well-preserved and continuous loess-paleosol sequences have been found recently in the Luonan Basin, offering an excellent opportunity to better understand monsoonal changes in the transitional climate zone of central China, as well as their specific influences on hominin occupation. The well-preserved Shangbaichuan (SBC) loess-paleosol sequence is representative of loess deposits in the Luonan Basin and, thus, an ideal archive for paleoclimate reconstructions (Lu et al., 2007, 2012; Sun et al., 2014).

Mineralogic and geochemical analyses of loess deposits enable correlations with likely source areas, elucidate secular variation within the loess sequence, and shed light on pedogenic weathering processes and paleoclimate changes (Yang et al., 2007a; Muhs et al., 2008; Jiang et al., 2016). In this study, we examined variations in clay and Fe-oxide mineralogy, elemental ratios, and a variety of element-based indices for pedogenic weathering in the SBC loess-paleosol sequence using X-ray diffraction (XRD), diffuse reflectance spectrophotometry (DRS), X-ray fluorescence (XRF), inductively coupled plasma-mass spectrometer (ICP-MS), and scanning electron microscopy (SEM). The objectives of this study were: 1) to determine which mineralogic and geochemical indices most effectively record variations in intensity of the EASM and EAWM; 2) to reconstruct variations in the EASM and EAWM since 870 ka within the transitional climate zone of central China; 3) to compare characteristics of the SBC sequence with coeval loess deposits on the CLP and in southern China in order to illuminate the climatic role of the Qinling Mountains; and 4) to elucidate possible relationships in timing and causality between tectonic uplift, changes in the EAM, and early human occupation of the Luonan Basin.

2. Geographical and geochronological background

The SBC loess-paleosol sequence (34° 04′ 03″ N, 110° 03′ 06″ E) is situated on the second terrace of the Shimenhe River, which is a tributary to the South Luo River, ~7 km west of Luonan County, Shangluo City, Shaanxi Province, central China (Fig. 1; Lu et al., 2007). The South Luo River flows eastward through the Luonan basin, before finally joining the Yellow River.

The Luonan Basin is located in a region with a generally warm and semi-humid climate. This basin is an intermontane depression with a surface elevation of ~990 m, a mean annual temperature (MAT) of ~11 °C, a mean annual precipitation (MAP) of ~705 mm (Lu et al., 2007). Loess-paleosol deposits in the Luonan Basin are distributed mainly on tablelands and river terraces, with total thicknesses ranging from 1 to 30 m, composed of several distinct loess-paleosol alternations (Lu et al., 2007, 2012; Zhang et al., 2012). The Luonan loess is harder (i.e., more firmly indurated) than that of the CLP, containing numerous black manganese oxides nodules and brown ferric oxide horizons (Zhang et al., 2012).

Many important and famous early to middle Pleistocene archeological sites (e.g., Dali and Lantian) are present in the vicinity of the Luonan Basin (Xiao et al., 2002; Bae, 2010; Yin et al., 2011). More than 90,000 stone artifacts, as well as one hominin tooth thought to belong to *Homo erectus*, have been reported from these sites (Xue, 1987; Wang et al., 2008; Bae, 2010).

The QMB, which is located dominantly in Shaanxi Province, central China, is situated on a tectonically active belt located between the Yangtze Craton and North China Craton. The QMB was formed by the collision of these continental plates during the Mesozoic (Meng and Zhang, 2000). The belt stretches for ~2200 km in a roughly east-west direction at an average elevation of ~2000 m. Field observations indicate that the SBC loess-paleosol sequence in the Luonan Basin is more intensively weathered than that of the CLP. The paleosols have a dark reddish-brown (5YR 3/6) to light reddish-brown hue (5YR 4/6), and the loess units show a light reddish-brown (7.5YR 5/8) to brown hue (7.5YR 5/6) (Table 1). The loess sequence consists mainly of wind-blown silt, with abundant pedogenic Fe and Mn concretions in the middle and lower parts (10.6–19.7 m) of the SBC study section (Fig. 2; Lu et al., 2007).

The age framework of the SBC sequence was established in earlier studies through magnetostratigraphic analysis, regional correlation of loess-paleosol layers, and OSL dating (Fig. 2; Lu et al., 2007, 2011). The Brunhes/Matuyama (B/M) boundary, which is dated to ~780 ka (Cande and Kent, 1995), has been identified at ~17.2 m below the top of the SBC profile (Fig. 2; Lu et al., 2007, 2011). Assuming a constant sedimentation rate above and below the B/M boundary, an age of ~870 ka for the base of the section was obtained by linear extrapolation (Lu et al., 2011). The SBC sequence has been approximately correlated with the Luochuan loess-paleosol sequence: (1) the uppermost four paleosols at SBC correspond to paleosols S1-S4 at Luochuan, and (2) the paleosol unit just below the B/M boundary at 17.2 m is equivalent to paleosol S8 at Luochuan (Lu et al., 2011). However, the SBC loess and paleosol units do not exactly match those of the Luochuan sequence on a