Journal of Asian Earth Sciences 155 (2018) 134–138

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

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

Full length article

A major change in precipitation gradient on the Chinese Loess Plateau at the Pliocene-Quaternary boundary

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ARTICLE INFO

Keywords:
Heavy mineral
QEMSCAN
Loess
Red clay
Precipitation
Quaternary
Pliocene
Hornblende weathering

ABSTRACT

Spatiotemporal variations in East Asian Monsoon (EAM) precipitation during the Quaternary have been intensively studied. However, spatial variations in pre-Quaternary EAM precipitation remain largely uninvestigated, preventing a clear understanding of monsoon dynamics during a warmer climatic period. Here we compare the spatial differences in heavy mineral assemblages between Quaternary loess and pre-Quaternary Red Clay on the Chinese Loess Plateau (CLP) to analyze spatial patterns in weathering. Prior studies have revealed that unstable hornblende is the dominant (~50%) heavy mineral in Chinese loess deposited over the past 500 ka, whereas hornblende content decreases to < 10% in strata older than ~1 Ma in the central CLP because of diagenesis. In the present study we found that hornblende is the dominant heavy mineral in 2–2.7 Ma loess on the northeastern CLP (at Jiaxian), which today receives little precipitation. Conversely, hornblende content in the upper Miocene-Pliocene Red Clay at Jiaxian is < 10%, as in the central CLP. The early Quaternary abundance of hornblende at Jiaxian indicates that the current northwestward-decreasing precipitation pattern and consequent dry climate at Jiaxian must have been initiated since ~2.7 Ma, preventing hornblende dissolution to amounts < 10% as observed in the central CLP. By contrast, the 7 Ma and 3 Ma Jiaxian Red Clay hornblende content is significantly less than that of the Xifeng samples, despite the fact that today Xifeng receives more precipitation than Jiaxian, with expected enhanced hornblende weathering. This suggests that the northeastern CLP received more precipitation during the Late Miocene-Pliocene than at Xifeng, indicating that the precipitation gradient on the CLP was more east–west during the Late Miocene-Pliocene rather than northwest-southeast as it was in the Quaternary. A comparison of magnetic susceptibility records for these sections confirms this inference. We attribute this major change in climatic patterns at ~2.7 Ma to decreased northward moisture transportation associated with Northern Hemisphere glaciation and cooling in the Quaternary. This study therefore demonstrates the potential usefulness of employing heavy mineral analysis in both paleoclimatic and paleooceanographic reconstructions.

1. Introduction

The Quaternary loess-paleosol and underlying Red Clay sequences on the Chinese Loess Plateau (CLP) represent a rich archive that can be used to reconstruct the evolutionary history of the East Asian Summer Monsoon (EASM) (Heller and Liu, 1982; Liu, 1985; An et al., 1990; Sun and Huang, 2006). While temporal variations in the EASM have been extensively studied (An et al., 1991; Ding et al., 1995; Guo et al., 2000; Lu et al., 2004; Sun and Huang, 2006; Sun et al., 2006a; Nie et al., 2014), knowledge of the spatial variations in the EASM through time remains limited because such work requires the comparison of results from a series of locations on the CLP. Based on meteorological station data, it is well known that modern EASM precipitation has a northwest-decreasing trend (Lu et al., 1994; Maher et al., 1994). As a result, studies trying to address the spatial patterns of the past EASM have often picked several sections along a north-south or northwest-southeast transect for study (Xiong et al., 2002; Yang and Ding, 2003). By comparing the pattern of magnetic susceptibility of soils deposited

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https://doi.org/10.1016/j.jseaes.2017.10.031
Received 13 September 2017; Received in revised form 27 October 2017; Accepted 27 October 2017

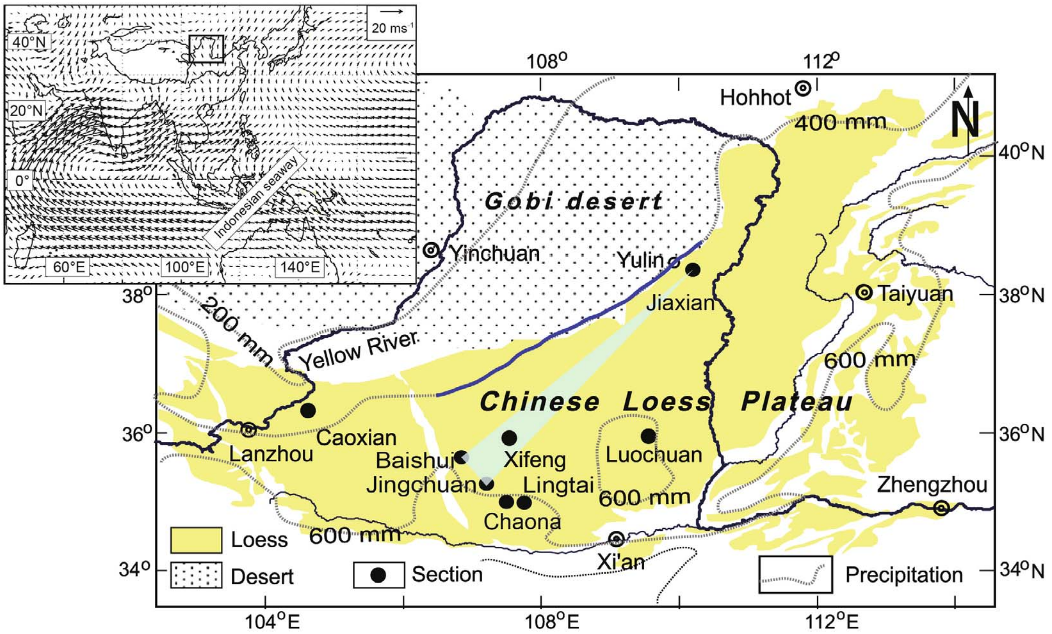

Fig. 1. Map of the study sites on the CLP. The inset map, revised from Clemens et al. (2008), shows the Asian summer Monsoon winds (arrows; m s^{-1}). Wind patterns (NCEP/NCAR reanalysis, 1951–2000) are from Wang et al. (2003).The main map is revised from Nie et al. (2013). Modern rainfall isolines are shown by dotted lines. The blue shaded area shows the proposed rainfall isoline range during the Late Miocene-Pliocene, as inferred from the magnetic susceptibility records, and heavy mineral data. The angle between the solid blue line and the blue shaded area shows the possible change in the isoline rainfall line angle between the Late Miocene-Pliocene and the Quaternary. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

simultaneously, a spatially northwest-decreasing EASM precipitation pattern similar to that of modern times has been inferred as having persisted back as far as 6 Ma (Xiong et al., 2002).

Although we largely agree with the general EASM precipitation pioneered by Xiong et al. (2002), we propose the possibility that the precipitation gradient was more east-west trending during the Late Miocene-Pliocene in comparison with the Quaternary, simply because the climate was warmer during the Late Miocene-Pliocene, and the sea surface temperatures (SSTs) of the western Equatorial Pacific Ocean were higher (Cane and Molnar, 2001; Fedorov et al., 2010). As a result of these higher SSTs, more moisture should have been transported from the western Equatorial Pacific Ocean to higher latitudes, increasing meridional precipitation, and resulting in the precipitation isoline in China having a smaller angle *versus* longitude in comparison with the Quaternary period, where moisture sources from the Indian Ocean are dominant (Fig. 1) (Clemens et al., 2008). Because the northeastern CLP is closer to the meridional transportation pathway for moisture sourced from the western Equatorial Pacific Ocean, it is important to include sites from the northeastern CLP when studying the spatial patterns displayed by EASM precipitation.

Professor Liu Tungsheng was a pioneer in the use of heavy mineral assemblages to understand the provenance history of Chinese loess. His work (Chapter 5 in his classic book "Loess and the Environment") encouraged us to pursue this direction, and to investigate whether paleoclimatic information can also be retrieved from the heavy mineral assemblages of loess and its underlying Red Clay deposited on the CLP. Our recent studies have demonstrated that the heavy mineral composition of pre-Late Quaternary loess and Red Clay on the CLP are affected by climate-driven diagenetic modification (Nie et al., 2013; Bird et al., 2015; Peng et al., 2016). Since unstable minerals are more rapidly destroyed in wetter and hotter climatic conditions (Van Loon and Mange, 2007; Andò et al., 2012; Nie et al., 2012; Garzanti et al., 2013), spatiotemporal changes in heavy-mineral assemblages contained in pre-Late Quaternary loess and Red Clay may yield important paleoclimatic information.

Here we investigate the stratigraphic trends during the period ~8–2 Ma in heavy mineral signatures in two crucial sections located at Jiaxian on the northeastern CLP, and at Xifeng on the central CLP. The heavy mineral data lead us to infer that Jiaxian may have received more precipitation than Xifeng during the Late Miocene-Pliocene, contrary to the pattern which characterized the Quaternary. We compare this heavy mineral data with published data from other sites and confirm the results of heavy mineral composition using published magnetic susceptibility records of Jiaxian and several other sites on the CLP (Sun et al., 1998; Qiang et al., 2001; Xiong et al., 2002; Yang and Ding, 2004; Sun et al., 2006b; Liu et al., 2008) (Fig. 1 and Table 1).

Table 1
Present-day mean annual temperature (MAT) and mean annual precipitation (MAP), and mean magnetic susceptibility (MS) values for 2.7–1.8 Ma and 3.5–2.7 Ma at the studied locations.

Section name	Annual mean temperature (°C)	Annual mean precipitation (mm)	MS (1.8–2.7 Ma)	MS (2.7–3.5 Ma)
Lingtai	8.8	650	96.25	157.53
Luochuan	9.6	610	70.52	
Chaona	9.0	600	74.67	117.46
Xifeng	8.7	555	52.08	70.91
Jingchuan	10.0	550	61.38	97.37
Baishui	8.6	500	40.03	63.55
Jiaxian	10.2	380	45.77	78.73
Caoxian	8.3	275		

2. Sites, materials and methods

Jiaxian (38°16′25″N, 110°5′25″E) is located on the northeastern CLP, east of the Mu Us Desert, with a mean annual precipitation (MAP) of ~380 mm (Qiang et al., 2001; He et al., 2015) (Fig. 1 and Table 1). Chaona and Luochuan, located to the south of Jiaxian, are both wetter than Jiaxian and have similar modern climate conditions with a MAP of ~600 mm (Fig. 1). Xifeng lies further northwest than Chaona and with a MAP of ~555 mm (Sun et al., 2006b) is drier than both Chaona and Luochuan, but wetter than Jiaxian. The MAP at Caoxian, further again to the northwest, is ~275 mm (Sun et al., 2006a). We collected 12 Red Clay samples and two loess samples from the Jiaxian section for heavy mineral analysis. The ages of the samples at Jiaxian are ~2 Ma, ~2.7 Ma, 3 Ma, 3.5 Ma, 4 Ma, 4.5 Ma, 5 Ma, 5.5 Ma, 6 Ma, 6.5 Ma, 7 Ma, 7.5 Ma, 8 Ma, and 8.3 Ma, based on paleomagnetic dating (Qiang et al., 2001). We did not collect new samples from the Chaona, Xifeng, Luochuan and Caoxian sections, but rather used previously published data which had been calculated using the same heavy mineral recognition techniques at Jiaxian (QEMSCAN: Quantitative Evaluation of Minerals by Scanning Electron Microscopy) (Nie et al., 2013; Peng et al., 2016), allowing meaningful comparisons. In addition, we compiled the magnetic susceptibility records of loess and Red Clay from Lingtai, Jingchuan, Xifeng and Baishui (Fig. 1) sections (Sun et al., 1998; Xiong et al., 2002; Yang and Ding, 2004; Sun et al., 2006b; Liu et al., 2008), and compared them with the loess and Red Clay magnetic susceptibility records from Jiaxian (Qiang et al., 2001).

The heavy mineral portions in the loess and Red Clay from the Jiaxian section were extracted using heavy liquid tribromethane (density 2.90 g/cm^3). Their compositions were recognized using the QEMSCAN technique at the Colorado School of Mines, USA. The details of these experiments have been described in previous publications (Nie et al., 2013; Nie and Peng, 2014). The number of heavy mineral grains counted in each sample ranged from 1300 to 12,000.

3. Results

The Jiaxian Red Clay heavy mineral assemblages are rather homogeneous and similar to assemblages from Chaona Red Clay, with dominant epidote and < 10% hornblende (Fig. 2 and Table 2). In contrast, the hornblende content from Jiaxian and Chaona samples was significantly lower than at Xifeng for both the upper (~3 Ma) and the lower (~7 Ma) Red Clay samples available from these two sections (Fig. 3 and Table 2). The 2 Ma loess sample from Jiaxian (L26) has high hornblende content (~60%), similar to that of loess and paleosol sediments deposited on the central CLP over the past 500 ka (Fig. 4 and Table 2), and significantly higher than the Mid and Early Quaternary samples from Luochuan, Chaona and Xifeng (Fig. 3). Since the samples did not show significant variations down section, we averaged L5 and L33 in order to compare this directly with loess layer L26 from Jiaxian (Fig. 3).

Although the upper Red Clay (3 Ma) samples from Luochuan, Chaona and Jiaxian all exhibit low hornblende content and similar heavy-mineral assemblages (Fig. 3), the hornblende content at Jiaxian is apparently higher than that at Luochuan and Chaona for lower Quaternary samples (L33), consistent with a decreased magnetic susceptibility after ~2.7 Ma at the site (Fig. 4 and Table 1). Before ~2.7 Ma, the magnetic susceptibility record within the section at Jiaxian is similar to that of Jingchuan, but higher than that seen at Xifeng and Baishui. After ~2.7 Ma, the magnetic susceptibility at Jiaxian changed to be systematically lower than that from Jingchuan, similar to Xifeng and Baishui (Fig. 4 and Table 1).

4. Discussion and conclusions

Prior studies have revealed easily-weathered hornblende to be the dominant (~50%) heavy mineral in Chinese loess on the central CLP over the past 500 ka (Nie et al., 2013). However, hornblende content decreases to < 10% in strata older than ~1 Ma in the central CLP because of diagenesis. With the paucity of any evidence of significant changes in provenance in mind (Sun, 2005; Pullen et al., 2011; Bird et al., 2015), such a marked decrease in hornblende has been ascribed to selective diagenetic dissolution (Nie et al., 2013). However, in the present study we also found that hornblende is the dominant (~50%) heavy mineral in loess dating to 2–2.7 Ma in the northeastern CLP (Jiaxian), which now receives little precipitation (Fig. 1 and Table 1). Well–preserved hornblende at Jiaxian, contrary to the inferred extensive dissolution of central CLP loess deposited during the Early Quaternary, would indicate limited climate-driven weathering during a period of dry climatic conditions on the northeastern CLP. We therefore conclude that a precipitation pattern spatially similar to the modern one was established by at least ~2.7 Ma.

By contrast, in older Upper Miocene to Pliocene (~3 Ma and ~7 Ma) Red Clay samples from Jiaxian, hornblende content is reduced and similar to that recorded for the central CLP at the same time, implying wetter Pliocene conditions similar to those of the central CLP. However, of particular note is that the hornblende content at Jiaxian is significantly less than contents at Xifeng (Fig. 3 and Table 1), where modern precipitation is currently higher than at Jiaxian. This reversed Pliocene hornblende pattern for Xifeng and Jiaxian implies that climatic conditions were wetter at Jiaxian than at Xifeng prior to

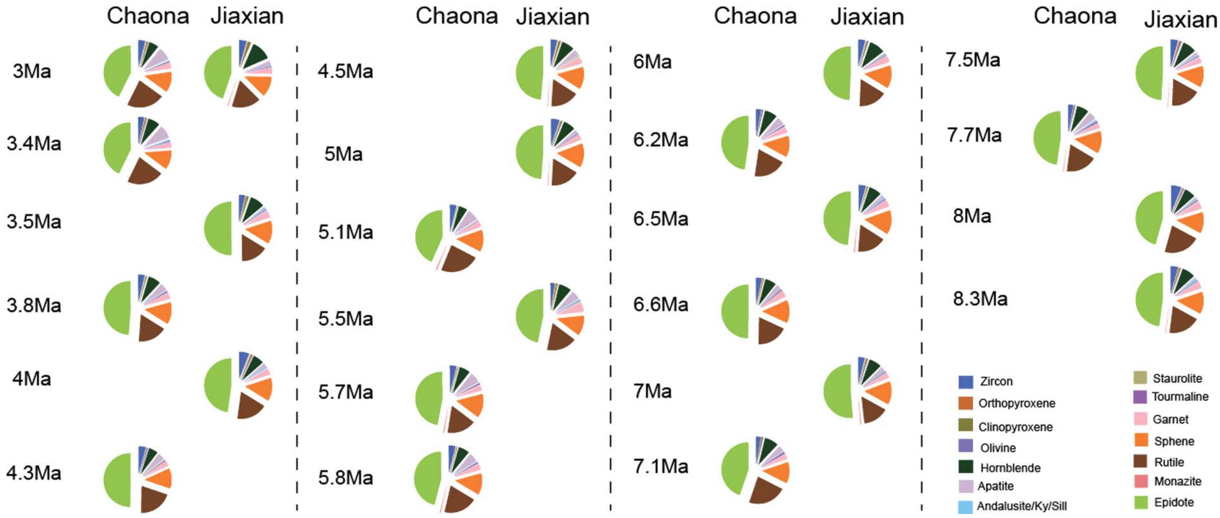

Fig. 2. Pie chart comparison of the heavy mineral assemblages found in Red Clay samples from Chaona and Jiaxian. Sill = Sillimanite, Ky = Kyanite.

Table 2
Heavy minerals in Jiaxian loess and Red Clay samples by volume (%).

	2 Ma	2.7 Ma	3 Ma	3.5 Ma	4 Ma	4.5 Ma	5 Ma	5.5 Ma	6 Ma	6.5 Ma	7 Ma	7.5 Ma	8 Ma	8.3 Ma
Zircon	1.13	1.61	4.49	3.59	5.96	3.92	4.93	2.46	4.05	4.33	3.92	4.51	6.18	4.58
Orthopyroxene	0.76	4.75	0.42	0.32	0.46	0.34	0.43	0.56	0.37	0.19	0.40	0.54	0.27	0.27
Clinopyroxene	4.58	6.31	1.44	1.24	0.62	0.96	0.58	0.48	0.68	0.56	0.54	0.58	0.27	0.49
Olivine	0.09	0.06	0.12	0.12	0.08	0.09	0.16	0.12	0.11	0.03	0.05	0.07	0.44	0.10
Hornblende	62.69	44.18	11.93	8.73	6.55	7.39	7.32	7.43	9.40	7.53	7.52	8.51	6.33	7.78
Apatite	2.39	2.15	2.50	0.83	1.54	3.30	1.47	5.32	0.72	1.60	2.21	1.65	1.00	0.92
Andalusite/Ky/Sill	0.20	0.33	0.37	0.57	0.78	0.36	0.67	0.77	0.52	0.75	0.72	0.79	0.61	1.09
Staurolite	0.12	0.63	0.10	0.07	0.09	0.07	0.13	0.10	0.09	0.14	0.09	0.08	0.25	0.02
Tourmaline	0.10	2.33	0.22	0.28	0.15	0.20	0.28	0.37	0.25	0.33	0.25	0.29	0.47	0.30
Garnet	2.24	11.63	3.68	4.38	3.86	3.79	3.34	5.72	3.81	4.00	3.58	3.13	4.58	4.25
Sphene	4.95	3.41	12.37	13.75	13.69	13.65	14.36	11.91	13.90	14.82	13.74	12.99	12.49	13.37
Rutile	6.72	4.01	17.19	15.77	18.38	17.17	17.29	18.00	16.68	17.12	15.43	17.50	21.46	18.73
Monazite	0.03	0.57	0.15	0.03	0.12	0.07	0.06	0.04	0.13	0.15	0.10	0.18	0.16	0.29
Epidote	14.00	18.05	45.02	50.33	47.72	48.68	48.99	46.71	49.31	48.47	51.45	49.17	45.50	47.80

The xMa represents the depositional age of each loess and Red Clay sample at Jiaxian, Sill = Sillimanite, Ky = Kyanite.

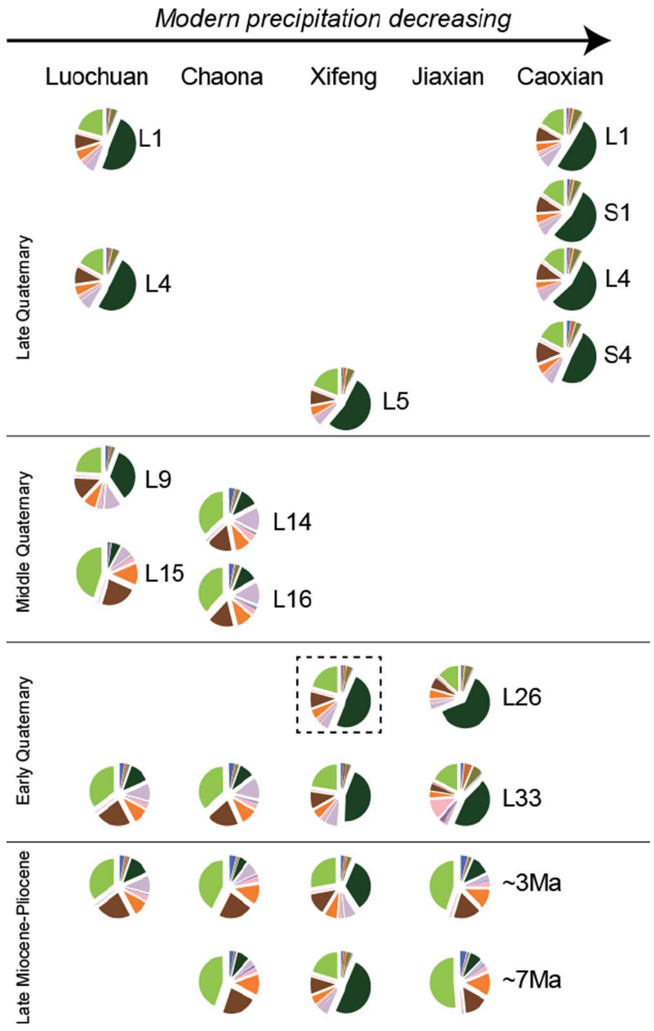

Fig. 3. Pie chart comparison of heavy mineral assemblages in loess-paleosol and Red Clay (~3 Ma and ~7 Ma) samples from the Luochuan, Chaona, Xifeng, Jiaxian and Caoxian sections. The mineral color coding is the same as in Fig. 2. The pie chart within the dashed square represents the average measurements between L5 and L33 found at Xifeng. Because L5 and L33 show similar heavy mineral assemblages, such an averaging is appropriate.

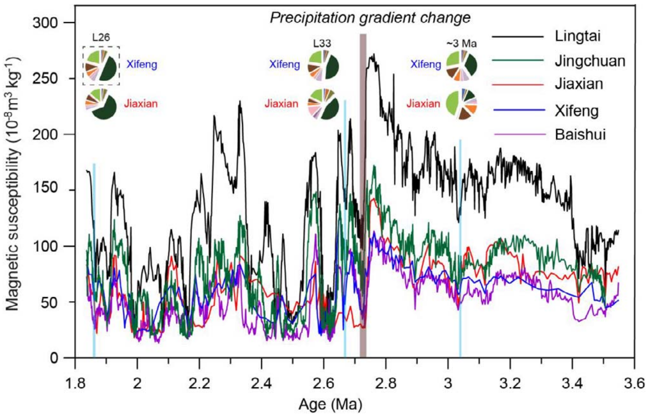

Fig. 4. Graphical comparison of magnetic susceptibility records for loess-paleosol and Red Clay samples from the Lingtai, Jingchuan, Jiaxian, Xifeng and Baishui sections (Sun et al., 1998; Qiang et al., 2001; Xiong et al., 2002; Yang and Ding, 2004; Sun et al., 2006b; Liu et al., 2008). Heavy mineral assemblages found in three samples (~3 Ma Red Clay, L33 and L26) from Jiaxian and Xifeng are also shown. The mineral color coding is the same as in Fig. 2. The light brown bar indicates the precipitation gradient change at ~2.7 Ma, as suggested by magnetic susceptibility analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

~2.7 Ma, and therefore indicates that a different rainfall gradient existed on the CLP compared to today, with wetter conditions further north and east in the Pliocene.

We tested this hypothesis by comparing magnetic susceptibility records of summer monsoon driven pedogenesis from different sections, all tuned to the Lingtai age model for consistency (Sun et al., 2006b). If the hypothesis above is to be corroborated then the Jiaxian magnetic susceptibility record from prior to ~2.7 Ma ought to show greater values than shown for the same period at the currently wetter central CLP sites (Fig. 1). Indeed, the magnetic susceptibility record observed at Jiaxian is similar to the record at Jingchuan section before ~2.7 Ma, but shows significantly higher values on average than at both Xifeng and Baishui sections (Fig. 4). Jingchuan is currently much wetter than Jiaxian and precipitation is also higher at Xifeng and Baishui today than at Jiaxian, thus supporting the inference based on heavy mineral assemblages. From ~2.7 Ma onwards, the magnetic susceptibility record at Jiaxian changed to be significantly lower values than that at Jingchuan, lying closer to that at Xifeng and Baishui (Fig. 4 and Table 1). As with trends in hornblende, this suggests relatively decreased precipitation on the northeastern CLP from this time, and marks the onset of the modern precipitation gradient in East Asia.

Several mechanisms could explain this trend to decreasing precipitation on the northeastern CLP during the Quaternary. First, paleooceanographic data suggested that the Pliocene was characterized by relatively warmer climate than the Quaternary (Molnar and Cane, 2002; Wara et al., 2005; Ravelo et al., 2006; Fedorov et al., 2010). In this situation, more heat and moisture could have been transported to higher latitudes via atmospheric processes (Molnar and Cane, 2002; Wara et al., 2005), causing the northeastern CLP to receive more precipitation due to its more proximate location to the meridional moisture transport pathway, and resulting in a more east-west precipitation gradient on the CLP. Second, the enlarged Eurasian ice sheets during the Quaternary enhanced the strength and persistence of the Siberia High (Ding et al., 1995), leading to intensified winter monsoon circulation and impeding the northward penetration of EASM circulation (Ding et al., 1995). Moreover, the decreased sea surface temperature and the reduced size of the West Pacific Warm Pool would also result in weakened EASM (Cane and Molnar, 2001; Fedorov et al., 2010).

While these are plausible mechanisms, the drivers behind the variations in the precipitation gradient over East Asia observed here require further research. Nonetheless, our study shows that the heavy mineral compositions in loess, paleosols and Red Clay may be useful as a proxy for climate change in dust deposit areas of East Asia. This opens up a new application for heavy mineral analysis in the potential retrieval of paleoenvironmental information from the sedimentary record, in addition to previous studies that mainly apply heavy mineral composition to infer sediment provenance/physical weathering information (Liu, 1985; Garzanti et al., 2013; Nie and Peng, 2014; He et al., 2017).

Acknowledgments

This paper is in memory of Professor Liu Tungsheng, “Father of Chinese loess research”. This work was financially supported by the National Key Research and Development Program of China (2016YFE0109500), the (973) National Basic Research Program of China (Grant No. 2013CB956400), the National Natural Science Foundation of China (Grant Nos. 41422204 and 41672157). We thank guest editor J. Sun and two reviewers for comments. We thank S. Yang for sharing the magnetic susceptibility data and Z. Liu for stimulating discussion.

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