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Spatially variable provenance of the Chinese Loess Plateau

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ABSTRACT

Loess sequences of the Chinese Loess Plateau (CLP) compose one of the most complete Neogene–Quaternary terrestrial paleoclimatic archives. Understanding the CLP's sediment sources is critical to tracing Asian aridification, atmospheric circulation patterns, and Asian monsoon evolution. Commonly, the sediments that compose the Quaternary strata of the CLP are considered largely homogeneous, and thus numerous studies have applied a uniform source model when attempting to use CLP-derived proxies as paleoclimate indicators. Here we present large-*n* detrital zircon U-Pb geochronology data from the Quaternary CLP. These data support spatial variability in sediment provenance across the CLP. At least three distinct provenance zones are recognized for Quaternary loess strata: central western, eastern, and northeastern. These zones received sediment primarily from their neighboring river systems. This finding conflicts with the classic views that attribute the Quaternary loess principally to the deserts north and west of the CLP. We conclude that fluvial processes, and thus precipitation, played an important and previously underemphasized role in Quaternary dust production in northern China. Furthermore, nonuniformity in CLP Quaternary sediment provenance raises questions about the validity of using paleoclimate information archived in the CLP to make sweeping regional interpretations.

INTRODUCTION

Loess deposits provide a window into past climates and environments (Liu, 1985; Li et al., 1988; An, 2000). To that end, various properties of loess have garnered attention as potentially useful paleoclimate proxies for desertification, atmospheric circulation, and regional dustiness, the latter of which can affect Earth's radiative forcing budget and ocean biogeochemical cycles. However, the usefulness of loess deposits as paleoclimate indicators is, in part, limited by our understanding of the transport pathways sediments took during dust production and deposition at the Chinese Loess Plateau (CLP) (Chen et al., 2007; Sun et al., 2008; Chen and Li, 2011; Pullen et al., 2011; Nie et al., 2015, 2018). For example, direct wind deflation of sediment from a proto-source would have much different paleoclimatic implications than sediment deflated from a riverine floodplain, the latter implying an important temporal and spatial relationship with precipitation in the production of dust (Amit et al., 2011; Nie et al., 2018).

The research discussed here addresses two fundamental questions about the nature of the CLP. Firstly, it is widely thought that eolian transport of dust to the CLP and deflation of those sediments from proximal deserts north and west of the CLP have largely resulted in a homogenous sediment provenance across the CLP (Jahn et al., 2001; Sun et al., 2008) (Fig. 1), with the possible exception of the Jingbian site (Bird et al., 2015) (Fig. 1). If relative homogeneity of the CLP is valid, it implies that paleoclimate interpretations based on the CLP can be more uniformly applied across the CLP, although wind sorting can potentially invalidate this application. Alternatively, spatial heterogeneity of provenance (Bird et al., 2015; Shang et al., 2016) implies that paleoclimate proxies across the CLP may be more locally unique than previously thought, thus undermining their usefulness without additional consideration for this spatial variability. Dust deposition across the CLP would have been dependent on sediment availability and surficial conditions in the locations that supplied sediment, which may or may not have responded uniformly to climatic forcing (Kocurek and Lancaster, 1999; Nie et al., 2015, 2018). Secondly, fluvial transport is widely considered in the dust production pathways of loess globally, e.g., Europe (Smalley et al., 2009), North America (Busacca et al., 2003; Muhs et al., 2018), South America (Zárate, 2003), and the Middle East (Crouvi et al., 2008; Muhs et al., 2014). However, riverine influences have largely been ignored for the CLP (Liu, 1985; Chen et al., 2007; Sun et al., 2008; Chen and Li, 2011; Pullen et al., 2011), with few notable exceptions (Stevens et al., 2013; Nie et al., 2015; Licht et al., 2016; Fenn et al., 2018).

In order to clarify sources of the Chinese loess, we report new zircon U-Pb ages in the western and northeastern CLP and compare these with previously published zircon U-Pb data (Table S1 and methods in the Supplemental Material[1]). We note that following the typical routine of detrital zircon U-Pb geochronology dating, zircons were dated randomly without selecting for size. To test relationships between the Quaternary CLP deposits and regional fluvial systems, we also report new zircon U-Pb ages

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[1]Supplemental Material. Materials and methods, Figures S1–S5, and Tables S1–S4. Please visit https://doi.org/10.1130/GEOL.S.14632965 to access the supplemental material, and contact editing@geosociety.org with any questions.

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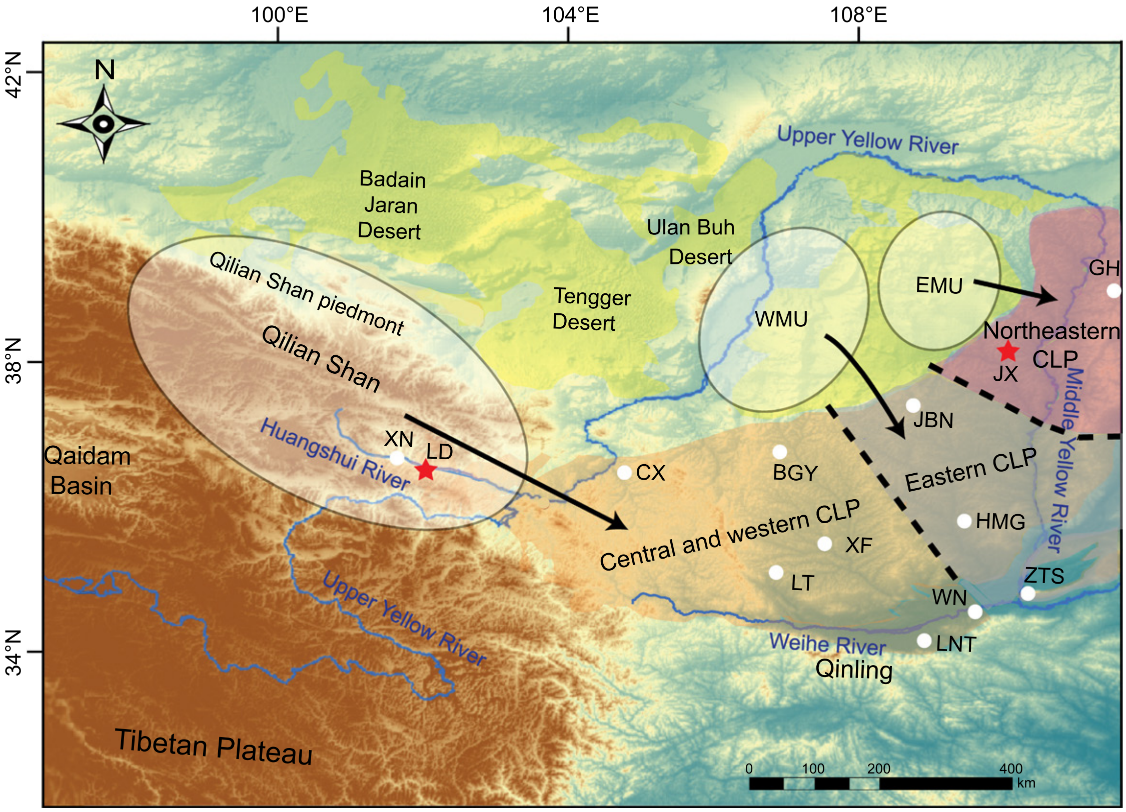

Figure 1. Map of detrital zircon sample sites in the Chinese Loess Plateau (CLP) and potential sources; modified from Wang et al. (2019). Two red stars indicate locations of the Ledu site (LD) and Jiaxian site (JX), for which we report new zircon U-Pb ages. White dots indicate locations of previously published loess zircon U-Pb sites (see Table S1 [see footnote 1]). Three white ovals indicate dominate potential sources for the central-western, eastern, and northeastern parts of CLP, respectively. XN—Xining; CX—Caoxian; BGY—Beiguoyuan; XF—Xifeng; LT—Lingtai; LNT—Lantian; HMG—Heimugou; WN—Weinan; JBN—Jingbian; ZTS—Zhongtiaoshan; GH—Gonghai; WMU—western Mu Us Desert; EMU—eastern Mu Us Desert.

from the Huangshui River draining the Qilian Shan and compile published zircon U-Pb ages from a wide range of potential loess source regions including northern China deserts, Yellow River sediments, Qaidam Basin sediments, and rivers flowing through the CLP (Fig. 1). Data from Quaternary loess samples in each site are combined for an overview of CLP provenance during the Quaternary and to satisfy the large-*n* data set requirement for performing a statistically adequate evaluation.

RESULTS

The probability densities, kernel density estimations, and histograms of U-Pb ages show three distinct provenance groups for the CLP (Fig. 2). The northeastern CLP is distinguishable by higher relative proportions of Paleoproterozoic zircons, which is similar to the age pattern of eastern Mu Us Desert and middle Yellow River sediments (Fig. 2). The eastern and central-western CLP are differentiable in terms of relative proportions of Paleozoic and Mesozoic zircon ages, with the eastern CLP having proportionally more Mesozoic ages and the central-western CLP having proportionally more Paleozoic ages (Fig. 2). This is similar to the detrital zircon U-Pb age pattern of upper Yellow River sediments and western Mu Us Desert, and that of the Qilian Shan and Huangshui River source region samples, respectively.

A multidimensional scaling (MDS) plot is an effective way of comparing dissimilarities in U-Pb data when the involved data set is large (Vermeesch, 2013; Saylor et al., 2018). A clear pattern emerges in MDS space: (1) data for the CLP distinctly cluster by region; and (2) regions are closest (i.e., least dissimilar) to their most proximal source areas (Figs. 3 and 4). The central-western CLP samples cluster together and plot close to Huangshui River sediments, Xining Basin sediments, and Qilian Shan piedmont samples. In contrast, the eastern sites cluster and plot closer to the upper Yellow River source area and western Mu Us Desert. The eastern CLP sites also plot closer to the middle Yellow River source area, eastern Mu Us Desert, and other northern China deserts than the central-western CLP sites. The northeastern CLP sites plot close to the middle Yellow River samples and eastern Mu Us Desert samples. The samples from the Lantian site show some similarity with other central-western CLP samples. However, this site also plots close to the northern Qinling and Weihe River samples (Zhang et al., 2018), making its distance a bit further in MDS space from the rest of the central-western CLP samples (Fig. 3). Guided by this pattern, we combine the central-western loess data together, excluding data from Lantian, and compare them with the combined data set of Huangshui River and Qilian Shan. We also combine data from the eastern loess sites together and compare them with the combined data set of upper Yellow River and western Mu Us Desert, and combine northeastern loess data together and compare them with the data from middle Yellow River and eastern Mu Us Desert samples.

Grain-size effects on detrital zircon ages should be acknowledged when comparing U-Pb data sets of this nature (Garzanti et al., 2009; Lawrence et al., 2011). The grain-size fractionation effects on age densities are insignificant here, for the following reasons. (1) The differences in grain size of the loess samples discussed here are smaller than those known to result in statistically significant differences in U-Pb age populations (Ibañez-Mejia et al., 2018). (2) Low-abundance age populations would be more adversely affected, as a percent change, by the grain-size age effect than high-abundance populations (Ibañez-Mejia et al., 2018). However, we compare major age modes here. This inference is reinforced by a comparison between two northeastern CLP samples (Jiaxian versus Gonghai sites) having different ages (early versus late Quaternary) and different analytical size minima (12 μm versus 30 μm). The zircon age pattern is strikingly similar for the two sites (Fig. S1 in the Supplemental Material). Further evidence comes from the Chaona site of the central CLP (Nie et al., 2018), where zircon U-Pb age distributions of the red clay sequences are similar for <20 μm and >20 μm populations (two red dots in Fig. S2). These lines of evidence suggest that the grain-size age effect is minimal for CLP loess samples because of minimal ranges in grain size.

We use the inverse Monte Carlo model (Sundell and Saylor, 2017) to determine the quantitative relative contribution of each potential source. Twenty-thousand (20,000) iterations of

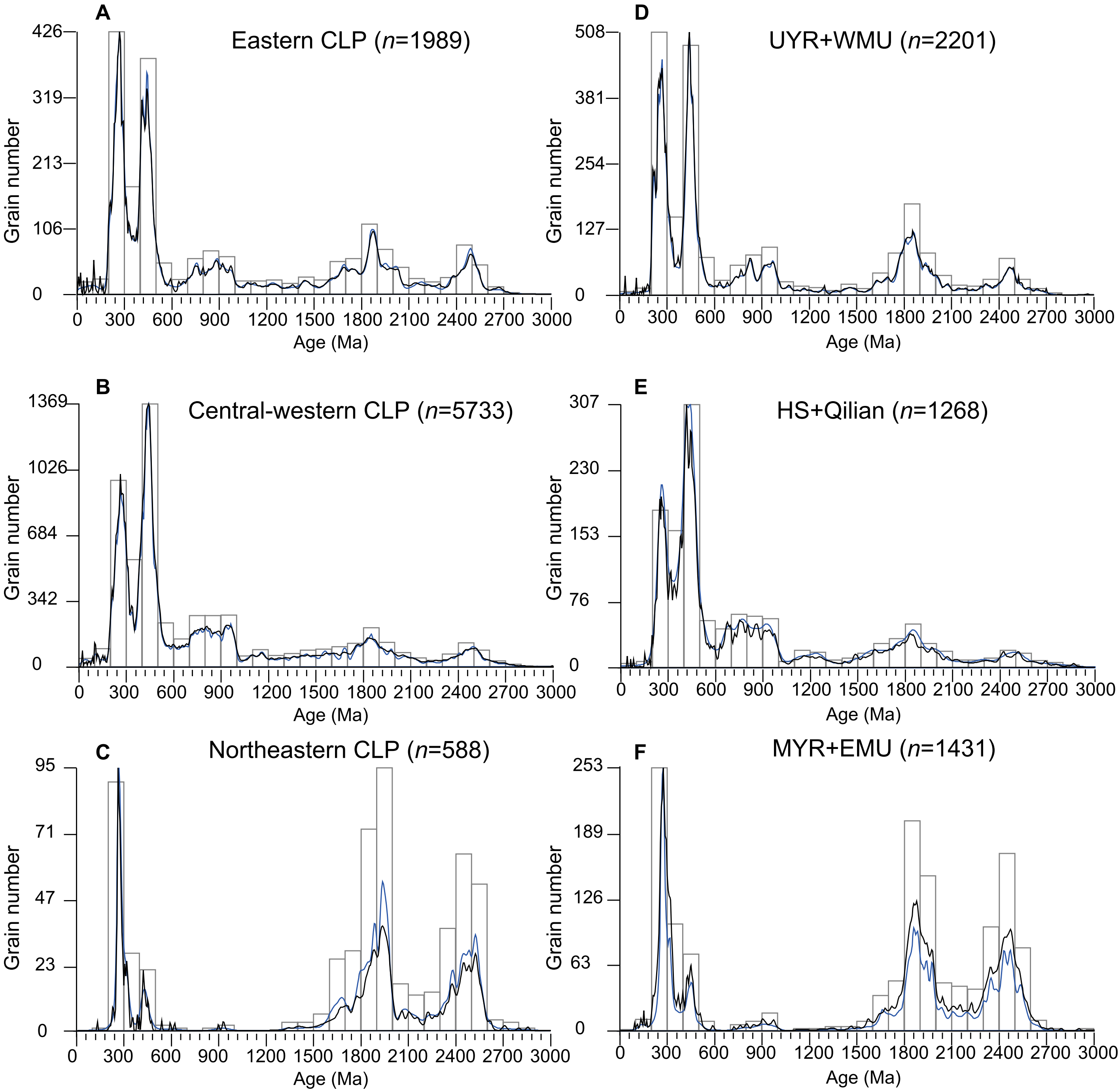

Figure 2. Visual comparison of detrital zircon U-Pb ages of combined data sets from Quaternary Chinese Loess Plateau deposits and potential sources (see Table S1 [see footnote 1]). Black and blue lines are normalized probability density plots (PDP) and kernel density estimation plots (KDE), respectively. Open rectangles are age histograms. (A) Combined data sets of eastern CLP. (B) Combined data sets of central-western CLP. (C) Combined data sets of northeastern CLP. (D) Combined data sets of upper Yellow River (UYR) and western Mu Us Desert (WMU). (E) Combined data sets of Huangshui River (HS) and Qilian Shan piedmont sediment (Qilian). (F) Combined data sets of middle Yellow River (MYR) and eastern Mu Us Desert (EMU).

fitting were performed to recover a particular detrital age spectrum by varying the contributions from the potential sources in order to match the zircon age spectrum for the CLP provenance zones with the best-fitting 1% selected (Table S2; Figs. S3–S5). The inverse Monte Carlo simulations suggest the Qilian Shan piedmont and Huangshui River samples contributed >70% to central-western CLP detrital zircons. The upper Yellow River and western Mu Us Desert samples contributed >50% to eastern CLP detrital zircons. The middle Yellow River and eastern Mu Us Desert samples contributed >90% to the northeastern CLP detrital zircons. These results provide further support for the observations made based on visual comparison of the probability and kernal density plots (Figs. 2–4) and the MDS plot.

SPATIALLY VARIABLE PROVENANCE OF THE CLP

Our large-*n* detrital zircon data set provides new insight into the provenance of the CLP. It is commonly assumed that the CLP loess is derived from the bounding northern China deserts (Liu, 1985; Chen et al., 2007) (Fig. 1). However, recent studies show that the upper Yellow River was involved in the production of dust deposited

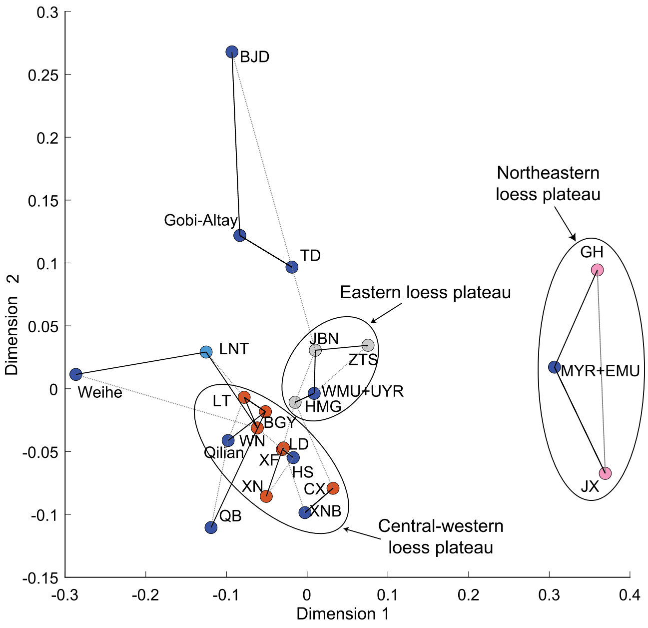

Figure 3. Non-metric multidimensional scaling (MDS) plot of zircon U-Pb age data of Quaternary loess sequences on the Chinese Loess Plateau (CLP) and comparison with potential sources. Brown, gray, and pink dots represent central-western, eastern, northeastern CLP samples, respectively (see Fig. 1 for site abbreviations). Dark blue dots are samples of potential sources. Light blue dot (LNT) represents the Lantian site, which is the southernmost site on the CLP examined here. Solid lines mark closest neighbors, and dashed lines, second-closest neighbors. Three black ovals depict clustered samples (see Table S1 [see footnote 1] for data sources). TD—Tengger Desert; BJD—Badain Jaran Desert; Qilian—Qilian Shan piedmont sediment; HS—Huangshui River sediment; XNB—Xining Basin sediment; QB—Qaidam Basin sediment; Weihe—Weihe River sediment; WMU + UYR—western Mu Us Desert and upper Yellow River sediment; MYR + EMU—middle Yellow River sediment and eastern Mu Us Desert.

on the CLP as the upper Yellow River carried northeastern Tibetan Plateau materials recognized in the CLP sediments (Bird et al., 2015; Nie et al., 2015; Licht et al., 2016). Additionally, it is assumed that the CLP loess is relatively homogeneous. Evidence presented here shows that the central-western CLP, the eastern CLP, and the northeastern CLP have distinct detrital zircon provenances. These provenances are associated with local fluvial systems or depositional zones within larger systems. These findings do not contradict the traditional view that northern China deserts are important sources for the CLP loess, but do point to the importance of precipitation, riverine transport, and floodplain deflation in the generation of dust deposited on the CLP. Deserts proximal to the CLP may have played an important role in contributing some of the finer sediments (<10 μm) to the loess (Cui et al., 2019)—we note that that provenance of the finer fraction cannot be addressed at this time using detrital zircon geochronology given current analytical limitations. However, because the >10 μm fraction composes the majority of loess sediments of the CLP (Sun et al., 2002), fluvial processes, and by extension the spatial and temporal distribution of precipitation driving fluvial transport and floodplain desiccation, must also be considered for models aimed at explaining Asia dust production (Yang et al., 2007). Therefore, past intervals with increased dust accumulation rates on the CLP are not necessarily indicative of desert expansion and/or enhanced aridity, but rather may point toward periods of high sediment mobilization to CLP source areas; this could, in part, reflect precipitation. Although enhanced precipitation is important for increase in eolian sediment supply, seasonal flows or extended periods of low flow are important for fluvial sediments to be deflated. The monsoonal climate is characterized by seasonally varied precipitation and flow. Therefore, the seasonally varied flow under a monsoonal climate would be ideal for dust production and deflation. Stevens et al. (2013), Nie et al. (2015), and Wang et al. (2019) attributed formation of the Mu Us Desert to drainage area expansion of the upper Yellow River associated with Asian monsoon intensification. Furthermore, recent wind-tunnel research in the Mu Us Desert and Tengger Desert shows that the sparse grasslands and coppice dunes showed as much as 5× greater dust-emission potential than the sand dunes (Cui et al., 2019). These studies are consistent with the ideas put forth here; however, like this study, they are more focused on the coarser sediment fraction. Future provenance studies would benefit from an integrated multiproxy approach.

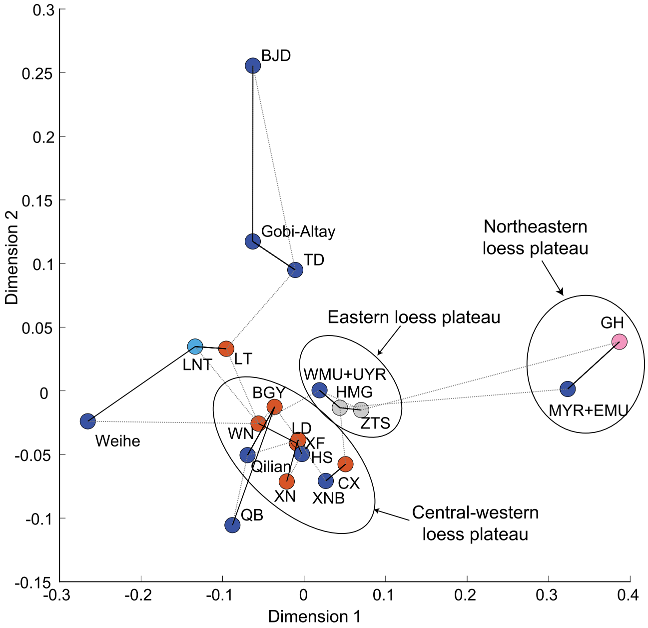

Figure 4. Non-metric multidimensional scaling (MDS) plots of Chinese Loess Plateau U-Pb age data from loess deposited since the last interglacial and comparison with potential sources. Abbreviations and symbols are the same as in Figure 3.

CONCLUSIONS

We conclude that Quaternary CLP strata have locally distinct provenance governed by proximity to three main source areas. Like other loess provinces globally, the CLP loess has a clear provenance link to fluvial activity within the dust production pathways. The spatial association between river systems and CLP loess provenance highlights the relevance of fluvial transport and the location and timing of precipitation in eastern Asia dust generation during the Quaternary. We conclude that fluvial activity plays a key role in loess accumulations globally.

Additionally, considering the lack of spatial uniformity in the detrital zircon provenance of the Quaternary CLP strata, we suggest caution when interpreting paleoclimate proxies archived within the CLP. Proxies like detrital biomarkers, grain size, or mass accumulation rates would be heavily affected by nonuniform sediment sourcing. The widely applied summer monsoon proxy from the CLP, magnetic susceptibility, which consists of a detrital and a pedogenic component, would be affected at levels worth considering. Importantly, once the nonuniform sediment sourcing is better understood, its impacts on paleoclimate proxies can be deconvolved from the proxies themselves, resulting in more accurate interpretations.

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