Insights into the Provenance and Spatiotemporal Variations of the Chinese Loess Plateau from Detrital Zircon Chronology (Postprint)

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Abstract

The Chinese Loess Plateau preserves the most extensive, thickest, and most continuous aeolian deposits in the world, serving as a highly valuable terrestrial archive of Quaternary paleoclimate and paleoenvironment. For over half a century, researchers have conducted extensive studies on the climate records preserved in aeolian deposits and the formation of the Loess Plateau. However, issues such as the exact provenance of loess dust and whether its provenance history has undergone spatiotemporal changes remain widely debated. Through statistical analysis of existing zircon age spectra data, with a focus on the genetic relationship between loess and surrounding deserts, orbital timescales, and tectonic timescales, the following conclusions have been reached: (1) Based on obtaining precise chronological information for deserts in the arid regions of northern China, application of the detrital zircon U-Pb age spectrum method is expected to achieve the long-term goal of clarifying the close versus distant provenance relationships between loess and aeolian sand. (2) Existing data identify that the provenance of L1 loess may exhibit spatial variations. (3) This supports the viewpoint that loess provenance did not undergo significant changes during glacial-interglacial periods. (4) On tectonic timescales, age spectra from different regions exhibit significant overlap in time intervals when provenance shifts may have occurred. (5) Limited red clay age spectrum data indicate that spatial differences in provenance likely existed prior to the Quaternary. Given that the current dataset is still limited, it is necessary to conduct further in-depth research. Application of this method enables investigation of the history of loess provenance changes on continuous long-term timescales and accumulates datasets for future multi-regional and multi-section provenance comparison work on the Loess Plateau.

Full Text

Understanding and Prospects of Provenance and Spatiotemporal Differences in the Loess Plateau Based on Detrital Zircon Chronology

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Abstract: The Loess Plateau of China preserves the most widely distributed, thickest, and continuous aeolian dust deposits in the world, representing a valuable geological archive of continental paleoclimate and paleoenvironment during the Quaternary. For over half a century, numerous studies have investigated the climate records preserved in these aeolian deposits and the formation of the Loess Plateau. However, the exact source of loess dust and whether temporal-spatial changes have occurred in its provenance history remain widely debated. Through statistical analysis of existing zircon age spectral data, this study focuses on the genetic relationship between loess and surrounding deserts from perspectives of orbital and tectonic timescales. The findings reveal: (1) Based on precise chronological information from deserts in the northern arid regions, the detrital zircon U-Pb age spectral method holds promise for clarifying the provenance relationships between loess and aeolian sand. (2) Current data identify potential spatial differences in the provenance of L1 loess from the last glacial period. (3) The viewpoint that loess provenance has not undergone significant changes during glacial-interglacial cycles is supported. (4) On tectonic timescales, the age spectra from different regions show overlapping periods when provenance shifts likely occurred. (5) Limited red clay age spectral data suggest that spatial differences in provenance probably existed before the Quaternary. Given the current scarcity of data, further in-depth research is necessary. Application of this method can investigate the history of loess provenance changes on a continuous, long-term scale and accumulate data for future multi-regional and multi-profile provenance comparisons across the Loess Plateau.

Keywords: detrital zircon U-Pb dating; source tracing; spatiotemporal differences; Loess Plateau

1 Provenance Linkages Between Loess and Northern Desert Complexes

The northern Loess Plateau is bordered by extensive Gobi desert belts that connect with the Central Asian arid region, forming the world' s only mid-latitude desert complex. Traditional tracing methods examining mineralogical characteristics such as grain size, dolomite content, and heavy minerals, quartz luminescence sensitivity, elemental and isotopic geochemistry, modern meteorological observations, and simulations have reached a relatively unified conclusion: loess dust deposits are genetically related to China' s northern desert complexes [?, ?]. Recent review articles also categorize the formation of the Loess Plateau as predominantly mountain-sourced [?]. However, serious disagreements emerge when addressing specific questions: Which desert is the loess source? Which deserts are the sources? When did these deserts become sources? For instance, some scholars argue that the provenance area of the Loess Plateau consists of proximal northern desert groups (mainly the Tengger and Badain Jaran deserts on the Alxa Plateau), while others contend that the primary sources are distal deserts in the Junggar, Tarim, and Qaidam basins [?]. The formation ages of these deserts remain controversial. The Tengger Desert' s formation has been constrained to the Quaternary (1.1-1.2 Ma) [?], while the Taklamakan Desert' s formation may date to 25 Ma [?]. If deserts are indeed the source areas for loess, a contradiction arises between the source area age and the loess deposition age, suggesting either that desert ages may be underestimated or that the relationship is more complex. Clearly, establishing precise chronologies for deserts is key to resolving this contradiction and enabling comparative studies of desert-loess provenance linkages.

The outstanding advantage of single-grain detrital zircon provenance tracing is its ability to directly identify the ultimate source of materials. To date, two major initial source areas have been reported in the literature: (1) the Central Orogenic Belt, Qilian Mountains, and nearby distal desert regions on the northeastern Tibetan Plateau margin, and (2) the Central Asian Orogenic Belt, Gobi-Altai Mountains, and nearby proximal desert regions [?]. Existing near-surface desert samples show strong genetic affinities with loess. For example, the Taklamakan Desert shares similar age spectral characteristics with loess, indicating they may have a common provenance [?]. Stevens et al. [?] compared age spectra of last glacial loess and surrounding deserts, concluding that the Qilian Mountains and Taklamakan Desert could be source areas. Subsequent work further distinguished between the western and eastern Mu Us Desert, suggesting that only the western portion served as a loess source [?]. The high degree of similarity between zircon U-Pb age spectra from Qaidam Basin sandstones and Heimugou glacial loess reflects a potential transport pathway where detrital materials from the northeastern Tibetan Plateau reached the Loess Plateau via the Qaidam Basin under westerly jet streams [?]. Thus, the zircon age spectral method not only breaks the assumption of a single dust source area but also establishes spatial linkages from erosion areas through intermediate deposition zones to terminal deposition zones, connecting orogenic belts, deserts, and loess. Age spectral characteristics clearly demonstrate genetic relationships among northern deserts, loess, and orogenic belts.

However, contradictions persist in identifying specific desert-loess connections. Che and Li [?] identified binary sources for Loess Plateau loess using zircon U-Pb ages, suggesting that the western Mu Us Desert may serve as a source via Yellow River transport, while the three distal basins (Junggar, Tarim, and Qaidam) do not. Fan et al. [?] proposed that the Tengger Desert and Qaidam Basin are the actual sources, with limited connection to the Taklamakan Desert —a conclusion supported by climate modeling results [?]. Some scholars disagree, arguing based on carbonate mineral content differences in <63 m fractions that the Taklimakan Desert is the primary source [?]. Others using Nd isotopic characteristics [?] or Sr-Nd isotopic evidence [?] also point to the Taklimakan Desert as the main loess source. Modern meteorological observations and simulations identify the Mongolian deserts, Taklimakan Desert, and Badain Jaran Desert as major sources [?]. Isotopic evidence indicates that the Qaidam Desert, Badain Jaran Desert, and Tengger Desert are the main sources for last glacial loess deposits [?]. Licht et al. [?] expanded the potential source area to include numerous deserts and Gobi regions, considering both primary (mountain bedrock) and secondary (sedimentary basins near source rocks) erosion, and correspondingly broadened the transport mechanism perspective from aeolian (primarily East Asian monsoon) to combined aeolian and fluvial processes (mainly the Yellow River and its tributaries).

Clearly, the focus of controversy centers on identifying specific desert-loess source connections. While loess basal ages are well-constrained at 2.6 Ma (with underlying red clay reaching 25-22 Ma), deserts lack effective chronological frameworks due to dating technique limitations. Among dated deserts considered potential source areas, the Badain Jaran Desert's formation is limited to the Quaternary (0.9 Ma), and the Tengger Desert' s environment may have formed at 1.1-1.2 Ma [?]. The controversial Taklimakan Desert may have formed at 25 Ma [?]. If deserts are loess source areas, the contradiction between source area age and loess accumulation age emerges, suggesting either underestimated desert ages or other complexities. Only by achieving precise desert dating can we establish comparative studies to resolve this contradiction.

The zircon age spectral method can serve as a link between orogenic belts, deserts, and loess, establishing spatial connections from erosion areas to intermediate and terminal deposition zones. With advances in desert chronology, future applications of this method can achieve comparisons of desert-loess provenance correlations and changes across different timescales. This not only resolves the aforementioned contradictions but also provides possibilities for discussing potential dust transport processes and pathways, offering new insights into reconstructing the evolution of the Tibetan Plateau' s basin-mountain geomorphological pattern. Some scholars have already begun investigating desert provenance change histories. For example, the Tengger Desert' s Quaternary zircon U-Pb age spectra show high matches with the Loess Plateau in multiple periods, with some intervals showing similar age spectral characteristics to the Qaidam Basin, indicating that the Tengger Desert' s main provenance may have changed during the Quaternary [?]. If deserts are loess source areas, the contradiction between source area age and loess accumulation age becomes apparent, highlighting the need for precise desert chronologies as the foundation for establishing desert-loess provenance comparisons.

2 Spatial Differences in Provenance of Last Glacial Loess L1

This study statistically analyzes published zircon U-Pb age data for last glacial loess from the main Loess Plateau region [?, ?] to discuss potential spatial differences in provenance under similar temporal constraints [Figure 1: see original paper]. Current data show that all regions exhibit distinct bimodal age spectra distributions between 0–600 Ma. Specifically, Caoxian, Xining, Lanzhou Yellow River terrace, Xifeng, and Weinan share similar bimodal patterns, with one peak at 100–350 Ma and a secondary peak at 350–600 Ma, characterized by a higher front peak and lower back peak [Figure 1: see original paper]. Lingtai and Lantian have a major peak at 100–350 Ma [Figure 1: see original paper]. Beiguoyuan has a major peak at 350–600 Ma and a secondary peak at 100–350 Ma [Figure 1: see original paper]. Heimugou shows a major peak at 350–600 Ma, similar to Lingtai and Lantian, but differs significantly from other regions in the 0–100 Ma and 600–2700 Ma ranges [Figure 1: see original paper]. Xining, Caoxian, and Lanzhou Yellow River terrace are all located west of the Liupan Mountains and share similar age spectral characteristics, possibly indicating the Tibetan Plateau as their common source.

Stevens et al. [?] delineated an east-west boundary line based on age spectral differences (green dashed line in [Figure 1: see original paper]), suggesting east-west provenance differences in the Loess Plateau. We also observed significant differences in age spectra east of the Liupan Mountains [Figure 1: see original paper], consistent with some scholars' views on north-south provenance differences [?]. Notably, Xifeng and Weinan, both east of the Liupan Mountains, exhibit two-peak patterns similar to loess west of the Liupan Mountains (Xining and Caoxian). This phenomenon matches the image features drawn using statistical methods by Bird et al. [?], though it remains unexplained. Current age spectral data indicate spatial provenance differences in last glacial loess, but limited data require further investigation.

3 Does Loess Provenance Change Between Glacial and Interglacial Periods?

Aeolian dust accumulation variations between glacial and interglacial periods directly reflect monsoon field conditions. Whether orbital-scale provenance changes occur remains debated. Some scholars argue that loess provenance may undergo cyclical changes due to variations in ground wind direction and strength between glacial and interglacial periods [?]. Others, citing mineralogical and geochemical characteristics and Nd isotopic signatures that remain stable across glacial-interglacial cycles, believe provenance has not fundamentally changed [?, ?, ?].

To clarify this issue, we collected zircon U-Pb age data from continuous stratigraphic positions of loess-paleosol sequences [?, ?, ?, ?]. Current zircon age spectra show [Figure 2: see original paper]: Except for significant changes in the primary peak morphology of Xining (S2-L2) and Beiguoyuan (S1-L1), other regions show only slight variations in the two-peak patterns without fundamental changes. The primary peak of Xining' s S2-L2 section nearly disappears [Figure 2: see original paper], while Beiguoyuan' s S1-L1 section shows an overall increase in the secondary peak [Figure 2: see original paper]. Weinan and Xifeng show no significant changes in their S1-L1-S0 sections. The secondary peak of Zhongtiaoshan increases in the 600-2700 Ma range, with minor differences in secondary peak distribution. Heimugou' s bimodal pattern remains fundamentally unchanged, with only slight variations in the 600-2700 Ma secondary peak.

Some studies attribute age spectral changes to "sampling effects," supporting the view that provenance has not fundamentally changed [?]. Bird et al. [?] used high-resolution sampling at Beiguoyuan, collecting 18 samples from the S9-L9 horizon, and found very similar age spectra between loess and paleosol units, concluding that provenance remained unchanged on orbital timescales and that secondary peak differences resulted from artificial statistical grouping.

However, sample size affects age spectral distribution characteristics, and insufficient statistical quantities may fail to reflect the true pattern. Vermeesch [?] suggested that approximately 1000 zircon grains are needed to identify each age component with 95% confidence. Notably, samples from Xining and Beiguoyuan with large primary peak variations have small sample sizes (n=61 for Xining S2-L2; n=94 for Beiguoyuan S1-L1), which may not reflect true age spectra. Additionally, Xining samples may be disturbed by human activity, potentially affecting results. The question remains whether these variations represent actual glacial-interglacial provenance changes or merely result from insufficient sampling.

To address this, we conducted regional classification statistics to ensure sufficiently large sample datasets (n 1000) and reduce statistical uncertainty [Figure 3: see original paper]. This approach also avoids concerns that "combining regional datasets may mask detailed spatial heterogeneity information." The existing dataset was divided into two groups: Group 1 (Jingbian, Beiguoyuan, Caoxian, Xining) and Group 2 (Xifeng, Lingtai, Heimugou, Weinan). Zircon age distribution characteristics show main peaks at 100-350 Ma and 350-550 Ma, with secondary peaks at 700-1100 Ma, 1700-2000 Ma, and 2200-2600 Ma. Both groups show good consistency in primary and secondary peak patterns, with no significant differences between loess and paleosol samples [Figure 3: see original paper]. The first group' s paleosol data proportion is slightly lower than loess, while the second group' s is higher [Figure 3: see original paper]. These differences may result from sampling effects. Overall, glacial-interglacial age spectra show no fundamental changes, supporting the view that loess provenance has not undergone major changes on orbital timescales.

4 Comparison of Loess Zircon Age Spectra on Tectonic Timescales

Investigating provenance issues of loess and underlying red clay on tectonic timescales helps understand the history and formation mechanisms of aridification in inland Asia. The tectonic timescale typically uses the 40 ka, 100 ka, and 100 ka cycles as reference frames. Records after 1.2 Ma include multiple glacial-interglacial cycles. On tectonic timescales, whether major provenance shifts occurred, when they happened, and their driving mechanisms are research priorities [Figure 4: see original paper].

4.1 Comparison of Quaternary Zircon Age Spectra from Different Profiles

Although Zhongtiaoshan and Heimugou have only one sample each in [Figure 5: see original paper], their age spectra differ significantly from underlying and overlying layers. Jingbian's L18 (1.4 Ma) sample shows a much higher secondary peak than other layers. Samples from L16-L8 (1.3-0.8 Ma) show similar overall age spectral patterns, distinct from L3 (0.3 Ma) layers. Lanzhou Yellow River terrace age spectra can be divided into three sections: T8 (1.7-1.5 Ma), T4 (1.2-0.9 Ma), and T2 (0.1 Ma). Unlike other profiles with bimodal patterns, Lantian shows multi-peak distributions in the <600 Ma range. Red clay and loess layers below 2.8 Ma commonly have a peak at 130-160 Ma that is absent in loess layers, indicating the North Qinling Mountains as a provenance area. The age spectrum at 2.8-2.5 Ma shows obvious differences [Figure 5: see original paper]. Limited data severely hinder full interpretation of loess stratigraphic information.

4.2 Comparison of Red Clay Zircon Age Spectra from Multiple Profiles

Red clay is an excellent record of late Tertiary paleoclimate changes [?], and its genesis history remains a research hotspot [?]. Several comparable red clay profiles exist using the zircon chronology method [Figure 6: see original paper]. Zhang et al. [?] divided the Chaona profile in Gansu into three periods using zircon age spectra from five horizons: (1) before 2.5 Ma from Liupan Mountains and Qaidam Basin; (2) 2.5-1.4 Ma mainly from Taklimakan Desert; (3) 1.2-0.9 Ma to present mainly from Qilian Mountains and Qaidam Basin, identifying a provenance change near 1.2 Ma. Shang et al. [?] compared red clay profiles from Baode (Shanxi), Lantian (Shaanxi), and Dongwan (Gansu), proposing different main provenance areas and transport dynamics. Lantian and Dongwan primarily sourced from the northeastern Tibetan Plateau margin and Taklimakan Desert, while Baode mainly sourced from the northern Central Asian Orogenic Belt, with corresponding aeolian transport by westerlies (low-level westerlies in winter monsoon) and northwesterly winds.

From the perspective of change timing, near-surface and younger strata (<0.06 Ma and <0.02 Ma) show varying degrees of change [Figure 5: see original paper]. Middle strata (0.9-0.15 Ma) show no significant changes at Zhongtiaoshan, Heimugou, Jingbian, Lanzhou Yellow River terraces, and Lantian. Older strata show very obvious changes in age spectra during the red clay-to-loess transition at Zhongtiaoshan L15-L9 and Lantian (2.8-2.5 Ma) [Figure 6: see original paper], indicating large-scale provenance shifts. This aligns with results from Nd isotopic methods [**?**]. Although different regions have different two-peak patterns, the timing of age spectral changes shows high overlap. This may mean that while loess main source areas have widespread spatial differences, the timing of changes is relatively consistent (0.9 Ma, 1.2 Ma, 2.5-2.8 Ma), matching the timing of intensified aridification in inland Asia.

Factors driving loess dust provenance changes are typically considered from tectonic and climatic perspectives. Climatically, the most recent large-scale global cooling occurred near 1.2 Ma (Mid-Pleistocene Revolution), when the Arctic ice sheet fully developed, global climate further cooled, and the dominant cycle shifted from 41 ka to 100 ka [**?**]. Tectonically, the phased uplift of the Tibetan Plateau since the Cenozoic significantly influenced the formation of Asian inland arid regions, establishment of the East Asian monsoon system, and generation of aeolian deposits [**?**, **?**, **?**]. Combined with the "episodic uplift" background of the Tibetan Plateau during the Quaternary, the change intervals in the above loess profiles match well with the "Kunlun-Huanghe Movement" (1.2-0.6 Ma) and "Gonghe Movement" (0.15 Ma-present) [**?**].

5 Prospects

1) **Multi-method integration for loess provenance tracing.** The single-grain zircon age spectral method has limitations regarding zircon grain size (current minimum laser beam diameter is 24 m), resulting in missing information for <24 m particles. Multi-tracer methods can provide effective supplements, including zircon image identification, heavy mineral assemblage characteristics, and Hf isotopes.

2) **Spatial differences in dust provenance.** Single-grain zircon age spectral methods have identified potential spatial differences in dust provenance across different Loess Plateau regions. Loess does not originate from a single source but generally shows mixed characteristics from multiple source areas. However, the features of these spatial differences require further investigation.

3) **Multi-regional, multi-horizon loess profile studies.** Particularly

lacking are high-resolution profiles on long timescales. Establishing multiple continuous long-sequence profiles in typical regions can use comprehensive comparison methods to reconstruct the spatiotemporal evolution of loess depositional environments.

4) **Chronological evidence for deserts.** Many deserts genetically linked to loess still lack precise chronological evidence. Once effective age frameworks are established for these deserts, comparative studies between deserts and loess on long timescales can be realized.

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Note: Figure translations are in progress. See original paper for figures.