Grain-Size End-Member Characteristics and Environmental Significance of the Aeolian Sand/Loess Deposition Sequence Since L2 in Hengshan, Shaanxi (Postprint)

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Abstract

Influenced by climate oscillations, desert boundaries have oscillated multiple times, leaving superimposed deposits of loess, paleosols, and paleo-aeolian sand in the strata. Through traditional grain-size parameters and end-member analysis modeling, this study investigates the grain-size composition, corresponding sedimentary information, and advance/retreat of sandy land contained in the aeolian sand–sandy loess–sandy paleosol sequence of the HS section at Hengshan, Shaanxi since L2. Results indicate that the grain-size composition of the HS section differs from that of typical loess regions, being dominated by very fine sand (31.07%), fine sand (30.20%), and coarse silt (23.38%), with a distinct characteristic of a wide grain-size range containing mixed coarse and fine fractions. Therefore, grain-size indicators with global paleoenvironmental significance in loess regions may not be suitable for this area; a parametric end-member analysis model was applied to decompose the local grain-size data, aiming to obtain climatic and environmental proxies appropriate for this region. Among these, end-member 1 (EM1) has a modal grain size of 8.93 m, reflecting information on westerly circulation; end-member 2 (EM2) has a mean grain size of 32.82 m, largely serving as an indirect indicator of East Asian winter monsoon intensity variations; end-member 5 (EM5) has a mean grain size of 235.46 m, representing a proxy indicator for extremely strong winter monsoons or severe storms, with its content reflecting the intensity of the winter monsoon at that time. Consequently, the study suggests that five episodes of sandy land expansion and three episodes of sandy land retreat have occurred at Hengshan, Shaanxi since L2, wherein aeolian sand layers accumulated during periods of strong winter monsoon conditions that triggered expansion of the Mu Us Sandy Land; when winter monsoon intensity weakened substantially, dune migration was replaced by dust accumulation, forming sandy loess layers; paleosol layers developed dur-

ing periods of relative winter monsoon weakening. Aeolian sand layers formed during glacial periods pose a non-negligible potential threat to current regional desertification, and protecting soil layers formed during the Holocene represents an important measure for preventing and controlling regional desertification.

Full Text

Characteristics of Grain Size End Members and Their Environmental Significance of Aeolian Sand/Loess Sedimentary Sequence Since L2 in Hengshan, Shaanxi Province

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Abstract

Climate oscillations have caused the desert boundary to swing back and forth multiple times, leaving overlapping deposits of loess, paleosol, and paleo-aeolian sand in the stratigraphic record. This study investigates the grain size composition, corresponding sedimentary information, and sand advance/retreat patterns of the aeolian sand–sandy loess–sandy paleosol sequence since L2 in Hengshan, Shaanxi Province, using traditional grain size parameters and end member analysis modeling. The results demonstrate that the grain size composition of the HS profile differs markedly from that of typical loess regions, being dominated by very fine sand (31.07%), fine sand (30.20%), and coarse silt (23.38%). Consequently, grain size proxies with global paleoenvironmental significance in loess regions may not be applicable to this area. A parameterized end member analysis model was employed to decompose the grain size data and obtain climate-environmental indicators suitable for this region. End member EM1, with a mode size of 8.93 m, reflects westerly circulation information. EM2, with a mean size of 32.82 m, largely serves as an indirect indicator of East Asian winter monsoon intensity changes. EM5, with a mean size of 235.46 m, represents a proxy for extremely strong winter monsoon or storm events, with its content reflecting the intensity of the winter monsoon at that time. The study concludes that since L2, Hengshan has experienced five sand expansion events and three sand retreat events. The aeolian sand layers accumulated during periods of strong winter monsoon when the Mu Us Desert expanded southeastward. When winter monsoon intensity weakened substantially, dune migration was replaced by dust accumulation, forming sandy loess layers. Paleosol layers developed when the winter monsoon was relatively weak. The aeolian sand layers formed during glacial periods pose a non-negligible potential threat to current regional desertification, and protecting the Holocene soil layers constitutes an important measure for preventing and controlling regional desertification.

Keywords: grain size; end member modeling analysis; climate change; sand advance and retreat; Hengshan

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Hengshan County in Shaanxi Province is located in the coupled zone between the Mu Us Desert and the Loess Plateau, representing the tail end of the East Asian monsoon region and responding sensitively to climate change. This location offers particular advantages for recording paleoclimatic and paleoenvironmental changes. The grain size composition and distribution characteristics are influenced by provenance, transport conditions, depositional environment, and post-depositional weathering, making them important for distinguishing depositional environments, determining transport modes and dynamic conditions, and reconstructing paleoclimatic environments. Aeolian deposits generally result from different provenances or depositional dynamic processes. Traditional grain size parameters such as mean size, mode, and skewness exhibit multiple solutions and uncertainties in environmental reconstruction studies. The grain size parameter characteristics of bulk samples can only approximately indicate changes in depositional environment. In contrast, end member analysis models can mathematically separate mixed-state sediments deposited under multiple dynamic processes into individual dynamic components, thereby achieving grain size component separation to further obtain sedimentary information reflected by individual dynamic components. Numerous studies have applied grain size end member analysis to various sediments, but its application to paleo-aeolian sand–sandy loess–sandy paleosol sequences remains relatively limited. Therefore, this paper attempts to use traditional grain size parameter research and end member analysis modeling to investigate the grain size characteristics of the L2 aeolian sand–loess sedimentary sequence in Hengshan, Shaanxi, seeking climate-environmental indicators suitable for this region' s characteristics to provide scientific support for regional environmental change studies.

1.1 Study Area Overview

Hengshan County, Shaanxi Province, is situated in the desert–loess transitional zone, with terrain sloping from higher elevations in the southeast to lower elevations in the northwest, at altitudes ranging from 900 to 1500 m. The region has a temperate continental monsoon semi-arid steppe climate, with a multi-year average temperature of 9.2°C and multi-year average precipitation of 355.9 mm. The annual average wind speed is approximately 2.4 $m \cdot s^{-1}$ (data from the China Meteorological Data Service Center annual dataset at //data.cma.cn/), with northerly winds prevailing and frequent sand-dust activities in winter and spring. The zonal vegetation is steppe, dominated by herbaceous plants with a small number of woody plants and semi-shrubs.

1.2 Study Profile

Through field investigation, a well-preserved aeolian sand-loess-paleosol profile was discovered approximately 15 km northeast of Hengshan County town, close to the southern margin of the Mu Us Desert, with continuous stratigraphy and clear horizons. This profile was designated as the HS profile, with a sampling thickness of [MATH_0] and a sampling interval of 15 cm. The profile bottom was not reached, yielding 64 samples. Field macroscopic observation revealed a 15 cm thick grayish-black silty fine sand layer with no bedding structure, containing a small amount of white calcareous pseudomycelia and relatively compact texture, which was identified as a paleosol layer.

1.4 Data Analysis

Grain size experiments were completed in the laboratory of the School of Geography and Tourism, Shaanxi Normal University. An appropriate amount of air-dried soil sample was weighed and placed in a beaker, then treated with 10% H_2O_2 and 10% HCl solutions, and heated on a hot plate until no small bubbles were produced to remove organic matter and secondary carbonates. After cooling, the beaker was filled with pure water and left to stand for 24 hours, after which the supernatant was siphoned off. Finally, a 0.05 $mol \cdot L^{-1}$ $(NaPO_3)_6$ solution was added as a dispersant, and the sample was ultrasonically oscillated for 10 minutes before measurement. Sample measurement was performed using a Mastersizer 2000 laser particle size analyzer with a single-range detection range of 0.02-2000 m and measurement error less than 1%. Each sample was automatically measured three times, and the average value was expressed as volume percentage.

Using China' s grain size classification standard, <5 m is clay, 5-10 m is fine silt, 10-50 m is coarse silt, 50-100 m is very fine sand, 100-250 m is fine sand, 250-500 m is medium sand, and >500 m is coarse sand. The graphic method and corresponding classification standards were used to calculate grain size parameters (mean size, sorting coefficient, skewness, and kurtosis). Grain size end member analysis was conducted using the MATLAB software package in the R environment. Under the assumption of Pater n end members, the profile grain size data were subjected to non-parametric and parametric decomposition, with the parametric method using Weilbull distribution functions.

2. Results and Analysis

2.1 Grain Size Characteristics

2.1.1 Grain Size Composition Characteristics The particle size composition of sediments is closely related to parent material and depositional environment, directly reflecting the content and distribution characteristics of mechanical components. Grain size analysis results show that the HS profile composition is dominated by very fine sand, fine sand, and coarse silt. Very fine sand content ranges from 2.60% to 53.30%, with an average of 31.07%; fine sand content ranges from 1.26% to 68.27%, with an average of 30.20%; and coarse silt content ranges from 4.72% to 66.60%, with an average of 23.38%. Other grain size components account for relatively small proportions throughout the profile.

For different grain size fractions, the clay content variation curve shows an opposite trend to very fine sand and fine sand contents, with the highest content appearing in paleosol layers (S1-1, S1-2), ranging from 1.35% to 15.66%. Sandy loess layers have the next highest content, fluctuating between 1.42% and 9.56%, while paleo-aeolian sand layers have the least clay content, averaging 4.44%. This indicates that weathering and pedogenesis gradually weaken from paleosol to sandy loess to paleo-aeolian sand. Fine silt variation is relatively small, ranging from 0 to 14.98%, with the highest content in paleosol layers (4.67%–13.68%, average 9.00%), followed by sandy loess layers (0–9.56%, average 4.67%), and the lowest in aeolian sand layers (0–2.63%, average 1.11%). Coarse silt shows large variation amplitude, with a minimum of 2.60% and maximum of 66.60%, averaging 23.38%. Its content variation trend across different strata is similar to fine silt, showing the pattern: paleosol layer > sandy loess layer > paleo-aeolian sand layer. Very fine sand content ranges from 2.60% to 53.30%, averaging 31.07%, while fine sand ranges from 1.26% to 68.27%, averaging 30.20%. Both show similar variation curves, with the pattern: paleo-aeolian sand layer > sandy loess layer > paleosol layer. Paleosol and sandy loess layers contain almost no medium or coarse sand, while medium sand in paleo-aeolian sand layers ranges from 0 to 27.29%, with an average of 10.15%.

Different horizons of the same sediment type also show differences in grain size distribution. For sandy paleosols, all layers are dominated by coarse silt (average 61.60%) and very fine sand (21.73%), with fine silt, clay, and fine sand accounting for less than 6.72%. Even during interglacial periods suitable for pedogenesis, sand particles still occupy considerable proportions. For sandy loess layers, grain size composition is dominated by coarse silt and very fine sand, with other components showing slight differences: L1-2 has more fine sand (26.94%) and less very fine sand (11.26%), while other sandy loess layers are dominated by fine sand (38.83%) and coarse silt (38.66%). For paleo-aeolian sand layers, grain size distribution is dominated by fine sand and very fine sand, with L2-4 and L2-2 having medium sand (19.86%) and fine sand (42.39%) as the main components, while other aeolian sand layers are dominated by fine sand (38.83%) and very fine sand (38.66%). Overall, the HS profile shows coarser grain size composition compared to typical loess plateau sequences.

2.1.2 Grain Size Parameter Characteristics The grain size parameters of the study profile are shown in Table 1. Mean grain size reflects the central tendency of grain size distribution, depending to some extent on the source material' s grain size distribution and the transport medium' s average kinetic energy. The overall mean grain size of the profile ranges from 29.02 m to 284.42

m, with a large fluctuation range and an average of 70.91 m, falling within the very fine sand range. Sandy paleosol layers have the smallest mean grain size, all within the coarse silt range, with S1-2 being the finest at 24.38 m. Paleo-aeolian sand layers have the largest mean grain size, ranging from 86.40 to 178.16 m, with the order: L1-2 > L1-1 > L2-2 > L2-5 > L2-4 > L2-3 > L2-1 > L2-6. Sandy loess layers fall between these extremes, with the largest mean grain size in L1-2 at 46.86 m.

The sorting coefficient characterizes the uniformity of grain size distribution, with smaller values indicating more concentrated grain size distribution and better sorting. The profile' s sorting coefficient ranges from 0.55 to 2.89, with an average of 1.64. Except for paleosol layers with sorting coefficients between 0.5 and 1 (medium sorting level), all other layers show poor sorting, indicating that HS profile sediments are generally poorly sorted.

Skewness reflects the symmetry of coarse and fine component distribution. The minimum skewness is 0.87 and the maximum is 2.63, with an average of 1.26. All layers show positive skewness except for paleosol layers which show extremely positive skewness, indicating that particle components are all concentrated toward the fine fraction.

Kurtosis characterizes the steepness of the distribution curve relative to a normal distribution. The profile's kurtosis varies between 0.87 and 3.17, with an average of 1.64, belonging to the leptokurtic category. Different sandy paleosol layers show wide kurtosis distributions. For paleo-aeolian sand layers, the grain size distribution morphology is basically consistent, showing a bimodal pattern.

2.1.3 Grain Size Curve Characteristics Grain size frequency distribution curves are commonly used to analyze particle size distribution and can infer depositional dynamics and provenance from peak attributes. In the HS profile' s grain size frequency curves (Fig. 5), the grain size distribution curves of the three sandy paleosol layers roughly coincide, with particle size concentrated in the coarse silt and very fine sand range, showing a bimodal pattern. The first peak appears at 5–30 m and the second peak at 50–75 m. The first peaks of S0, S1-1, and S1-2 largely overlap, while the second peaks differ slightly, with peaks gradually decreasing and curves shifting toward coarser particles. Different sandy loess layers show basically consistent grain size distribution ranges, with a symmetric distribution and mode diameters between 50–100 m, decreasing toward both coarse and fine ends centered on the mode. The decrease toward the coarse end is relatively smooth, while the decrease toward the fine end is not smooth, with an obvious platform at 5–50 m. For paleo-aeolian sand layers, the grain size distribution morphology is basically consistent, showing a bimodal pattern with the first mode at 75–250 m and the second mode at 5–30 m, with the second mode gradually decreasing.

The grain size cumulative distribution curves (Fig. 5) clearly show that fine particle cumulative content increases in paleosol layers (S0, S1-1, S1-2) compared to other strata, reflecting increased clay content during paleosol formation. In sandy loess layers, except for L1-2 which has a smaller cumulative curve slope, the slopes of other layers are basically consistent, though L1-2 is more biased toward the fine fraction. The grain size cumulative curves of paleo-aeolian sand layers all show an obvious bulge between 50–250 m, representing saltation components. EM1 shows the smallest slope in the cumulative curve across the profile, indicating poor sorting.

2.2 Grain Size End Member Separation of the Study Profile

Different grain size ranges respond to climate change differently. Due to Hengshan's special geographical location in the desert–loess transitional zone, its grain size composition differs significantly from the Loess Plateau region. Therefore, grain size proxies with global paleoenvironmental significance in the loess region may not be suitable for this area, making it important to separate grain size indicators for further investigation of sediment grain size composition origins.

2.2.1 End Member Grain Size Characteristics The weak sorting of the HS profile grain size indicates multiple genetic components. End member separation was performed, and parametric end member analysis results are shown in Fig. 6. When the number of end members is 5 and the angle deviation is 10°, the dataset' s multiple correlation coefficient R^2 reaches 0.99, indicating excellent overall fit. Therefore, five end members were selected as the optimal fitting result, designated EM1-EM5. The grain size distribution results for each end member are shown in Table 2.

From the separated five end members' grain size frequency distribution curves (Fig. 7), EM1, EM2, and EM3 show relatively sharp peaks with better sorting, while EM4 and EM5 have larger grain size distribution ranges with poorer sorting. Additionally, from the probability cumulative curves of each end member (Fig. 7), EM1 consists of two suspension components, EM2 and EM3 consist of suspension and saltation components, and EM4 and EM5 consist of saltation and traction components.

2.2.2 End Member Content in Different Strata Separating grain size components from sediments deposited under different provenances and conditions helps explain their different origins and better reconstruct paleoenvironmental changes in this region based on their depositional sequences. The variation curves of each end member with profile depth are shown in Fig. 8.

EM1 content varies from 0 to 64.50% across the profile, with a maximum of 21.29% and an average of 17.19%. EM2 content varies between 21.51% and 93.06%, with an average of 74.50%. EM3 content varies from 0.89% to 39.91%, with a maximum of 99.97% and an average of 76.49%. EM4 content varies from 3.17% to 158.87%, with a minimum of 40.02% and an average of 53.21%. EM5 content varies from 15.89% to 200.00%, with a minimum of 34.92% and an average of 42.27%. Different end members show different characteristics in different strata.

EM1 content is highest in paleosol and sandy loess layers, reaching 57.50% in S1-2. EM2 content is highest in paleo-aeolian sand layers, ranging from 71.50% to 96.23% with an average of 88.62%, while it is lowest in paleosol layers (34.92%) and moderate in sandy loess layers (47.70%). EM3 content is highest in sandy loess layers (47.01%) and lowest in paleo-aeolian sand layers (5.11%). EM4 content is highest in paleo-aeolian sand layers (65.76%) and lowest in paleosol layers (14.15%). EM5 content is highest in paleo-aeolian sand layers (71.33%) and lowest in sandy loess layers (12.98%). Notably, the grain size distribution ranges of EM4 and EM5 overlap, and their contents are consistent in paleosol and sandy loess layers, with slightly increased content in paleo-aeolian sand layers.

3. Discussion

3.1 Environmental Significance of Grain Size End Member Components

The mode particle size of EM1 is 8.93 m, belonging to the fine silt fraction. In general, fine particles in aeolian deposits have three sources: (1) transported and deposited by wind; (2) adhered to coarse particle surfaces or transported and deposited as particle aggregates; and (3) secondary components produced by weathering and pedogenesis after deposition. Weathering and pedogenesis can produce fine particles, but typically with sizes <2 m. The component with a mode size of 8.93 m in EM1 can exclude the possibility of being transported as aggregates or attached to coarse particles, nor is it a product of weathering and pedogenesis. It is more likely transported over long distances by high-altitude airflow.

Atmospheric dynamics studies indicate that fine silt components in the 2–10 m range can be transported to the upper atmosphere by wind and remain suspended for long periods. The probability cumulative curve of EM1 shows that only EM1 contains long-term suspension components. The westerly belt is an important component of the Northern Hemisphere mid-latitude atmospheric circulation system. Under the action of high-altitude westerlies, fine components are continuously delivered to this region, with their content mainly depending on the background dust concentration in the atmosphere determined by source area aridity. Fine dust carried by high-altitude westerlies can be deposited through precipitation. Studies show that in the Loess Plateau region, components with mode diameters in the 2–8 m range are considered to be transported from distant sources by large-scale high-altitude circulation and deposited continuously throughout the year. In Tajikistan loess, end member components with mode diameters of 2–8 m are also transported by high-altitude westerlies and can record climate fluctuations in the North Atlantic region. Therefore, EM1 likely reflects westerly circulation information, providing a relatively stable background value for atmospheric dust.

EM2 has a mean size of 32.82 m, belonging to coarse silt. Components with a mean size of 32.82 m are mainly transported in suspension and can rise to several hundred meters near the surface during typical dust storms, with transport distances of approximately 1000 km. Winter half-year is the main dust-fall season in the study area, with the East Asian winter monsoon dominating near-surface airflow. This component constitutes the main part of paleosol and sandy loess layers in the study area, with content ranging from 72.90% to 85.88%. Correlation analysis between each end member component and mean grain size shows that EM2 has the most significant correlation ($R^2 = 0.60$), while EM1 shows a weaker correlation ($R^2 = 0.52$). These results reveal that EM2 is largely an indirect indicator of East Asian winter monsoon intensity changes, with its content feeding back the intensity of the winter monsoon at that time. In Prins and Vriend' s studies, components with mean sizes around 20 m transported by short-distance suspension were considered winter monsoon proxies. In Sun Donghuai et al.' s research, coarse components in Chinese loess with mean sizes between 21–54 m were considered winter monsoon proxies. Although weathering can produce fine particles, it typically generates particles <2 m. Therefore, the content changes of EM2 may not be explained by weathering processes alone. The fact that EM2 content shows positive correlation with winter monsoon intensity indicates it is carried and deposited by the winter monsoon, with short transport distances and low suspension heights. Notably, grain size indicators that are negatively correlated with winter monsoon in the Hengshan area are positively correlated in the loess region, consistent with Yang Lirong' s research conclusions.

EM4 has a mean size of 132.26 m and EM5 has a mean size of 235.46 m, both belonging to fine sand fractions. In typical dust storm events, coarse components (70–500 m) can only rise to a few centimeters to meters above the surface and saltate horizontally for similar distances. This component represents locally formed aeolian sand. In strata deposited during the last glacial period, all layers are paleo-aeolian sand layers, but the contents of the five end members in these sand layers differ. EM5 content shows the strongest positive correlation with mean grain size ($R^2 = 0.60$), indicating more intense winter monsoon during glacial periods. Notably, the thick aeolian sand layers in this study area reflect large-scale expansion of the Mu Us Desert at that time, but their EM5 content is lower than in the relatively warm and humid stage. Comparing the three paleo-aeolian sand layers, EM5 contents differ, with L2-4 having the highest content (92.85%) and L2-2 the lowest (71.50%), indicating that winter monsoon intensity also varied during the same period. For sandy loess layers, EM5 content is lower than in paleosol layers but higher than in sand layers, forming when dune activity was replaced by dust accumulation as winter monsoon weakened, but still dominated by winter monsoon conditions.

Through the study of grain size end member characteristics of sediments since L2 in Hengshan, Shaanxi, the main grain size components of both glacial sandy loess layers and interglacial sandy paleosol layers fall within the near-surface short-distance saltation range. This difference is not solely caused by wind sorting but may more directly reflect the influence of the source area. Without proximity to desert sources, such large quantities of coarse particles could not be deposited. The desert-loess transitional zone shows obvious superiority and sensitivity in recording desert changes compared to the Loess Plateau, while also effectively recording the fluctuation history of winter monsoon intensity.

3.2 Grain Size End Member Records of East Asian Winter Monsoon Changes

In the desert-loess coupled system, the winter monsoon or strong storms are the main climatic elements affecting its changes. Dry and strong winter monsoons cause sand particle activation and desert range expansion, while the transitional zone is the direct product of this change process. The variation curves of EM2 and EM5 are good records of winter monsoon changes in Hengshan, with EM2 negatively correlated with winter monsoon changes and EM5 increasing with winter monsoon enhancement.

The troughs and peaks in the EM5 variation curve indicate the intensity and duration of winter monsoon, reflecting large-scale desert expansion during the same period. This is because expanded high-latitude ice sheets in the Northern Hemisphere during glacial periods injected cold air masses into downstream areas, strengthening the Siberian High. The coupling between the Siberian High and the Aleutian Low in the Northwest Pacific led to enhanced northwest winter monsoons. This strengthened cold and dry wind favored southward desert extension and increasing dust transport to the desert-loess transitional zone. The overall desert expansion during glacial periods had a significant impact on grain size in the transitional zone. In extreme cases, when desert expansion reached the study area, EM5 content reached 91.26% and EM2 content was below 45.62%. During interglacial periods, EM5 content decreased to 47.01% and EM2 content increased to 86.60%, indicating that desert range contracted significantly compared to glacial periods and winter monsoon intensity weakened substantially.

The grain size curves of sediments deposited during the last interglacial period (S1) show high-frequency, low-amplitude oscillations against a background of overall grain size fining, reflecting unstable winter monsoon during the overall weakening process. The transition from the last interglacial to the last glacial was abrupt, indicating rapid and obvious winter monsoon effects during climate cooling periods.

The HS profile consists of 2 paleosol layers and 5 aeolian sand layers interbedded with 4 loess layers. Compared with the Yulin Caijiagou profile, which consists of 2 paleosol layers interbedded with 3 aeolian sand layers and 4 loess layers, the difference may be related to the position shift of the desert-loess transitional zone. As the HS profile is located further south, the desert may not have reached this location during expansion periods, or erosion and depositional hiatus may have occurred due to different geomorphological positions.

3.3 Regional Desertification

The differences in grain size composition of sediments since L2 in Hengshan, Shaanxi, reflect the impact of climate change on the regional environment. When climate is relatively warm and humid, the Mu Us Desert and the southern desert-loess transitional zone develop sandy grasslands, forming sandy paleosols on the surface. When the East Asian winter monsoon strengthens, surface vegetation degrades, fine soil particles are blown away, desertification develops rapidly, the Mu Us Desert becomes active and expands to the northern Loess Plateau, leaving thick aeolian sand layers on the transitional zone surface.

The HS profile shows that paleo-aeolian sand layers are mainly composed of fine sand and very fine sand, almost without clay, while sandy loess and paleosol layers have much smaller grain sizes with greatly increased silt content. These overlying layers cover the lower paleo-aeolian sand layers, playing a stabilizing and protective role. However, the Ordos Plateau where the Mu Us Desert is located has experienced intermittent uplift during the Cenozoic, causing strong erosion by plateau water systems. River downcutting has promoted the development of more gully systems, potentially exposing paleo-aeolian sand layers covered by thicker soil layers and providing material basis for wind erosion, posing a potential threat to regional desertification. Meanwhile, unreasonable human cultivation and grazing can also activate paleo-aeolian sand. Therefore, protecting Holocene soils is an important measure for preventing regional desertification in this area.

4. Conclusions

Based on the grain size characteristics and end member analysis of the paleo-aeolian sand, sandy loess, and sandy paleosol sequence in the desert-loess transitional zone of the HS profile, the following conclusions can be drawn:

1) The grain size composition of the Hengshan paleo-aeolian sand-sandy loess-sandy paleosol sequence differs significantly from the loess-paleosol sequence of the Loess Plateau region. The average content order of the HS profile is very fine sand (31.07%) > fine sand (30.20%) > coarse silt (23.38%) > medium sand (6.72%) > fine silt (4.67%) > clay (2.89%). For sandy paleosol layers, coarse silt and very fine sand are the dominant fractions, with mean grain size being the smallest. Sandy loess layers are dominated by coarse silt and very fine sand. Paleo-aeolian sand layers in L1-2 are dominated by fine sand and very fine sand, while those in L2-4 and L2-2 are dominated by fine sand and medium sand, with overall coarser grain size.

2) Five end members were separated through parameterized end member analysis. EM1 (mode size 8.93 m) represents far-source dust transported

by high-altitude airflow under westerly belt control. EM2 (mean size 32.82 m) is mainly transported in suspension and serves as an indirect indicator of the East Asian winter monsoon. EM5 (mean size 235.46 m) is a direct product of extremely strong winter monsoons and serves as a grain size-sensitive component for paleoclimatic changes in this region.

3) Paleo-aeolian sand layers are products of regional intermittent arid conditions controlled by winter monsoon, reflecting the southeastward extension process of the Mu Us Desert. When regional climate was still dominated by winter monsoon but with greatly reduced intensity, dune migration was replaced by dust accumulation, forming sandy loess layers. When active dune migration or rapid dust accumulation was replaced by geomorphological stability and pedogenesis, sandy paleosol layers formed. Grain size curves indicate that significant second-order climate oscillations occurred during both glacial and interglacial periods.

4) Since L2, Hengshan has experienced five sand expansion events and three sand retreat events. Aeolian sand layers accumulated during periods of strong winter monsoon when the Mu Us Desert expanded. Paleosol layers developed when winter monsoon was relatively weak, while sandy loess layers were deposited during transitional climate states.

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