OSL Dating of a Typical Aeolian Sedimentary Profile in the Mu Us Sandy Land since 12.6 ka and Its Significance: Postprint

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Abstract

The Mu Us Sandy Land exhibits high sensitivity to global climate change, with its aeolian sand-paleosol sequences primarily influenced by the East Asian monsoon circulation system. However, the response of sandy land environmental evolution to monsoon changes demonstrates nonlinear characteristics at local scales, introducing uncertainties into the reconstruction of regional climate and environmental changes based on aeolian deposits. This study conducted systematic optically stimulated luminescence (OSL) dating analysis on eight aeolian sediment samples from three sections in the Mu Us Sandy Land, with results indicating: (1) The sections deposited aeolian sand layers at approximately 12.6 ka and 0.1 ka, while paleosol layers developed at approximately 6.9 ka and 9.6-4.2 ka, corresponding to relatively dry-cold climate and the warm-humid climate of the Holocene Megathermal period, respectively, revealing that sandy land deposition is influenced by climate change. (2) At approximately 12.6 ka, the southeastern section of the sandy land developed typical aeolian sand layers, whereas contemporaneous central region sections showed no aeolian sand deposition records, which may be related to wind strength variations induced by regional topographic gradients and local geomorphological differences. (3) The similarities and differences in the initiation and cessation timing of paleosol development in hinterland sections of the sandy land may be associated with comprehensive factors including local ecological processes, topography and geomorphology, and climatic events. (4) The absence of mid-to-late Holocene sediments in the southeastern section of the sandy land may be related to regional fluvial erosion; whereas the relatively young aeolian sand layers deposited in the upper parts of central region sections may be associated with enhanced aeolian activity resulting from regional climate aridification trends.

OSL Dating of Typical Aeolian Deposition Profiles in the Mu Us Sandy Land since 12.6 ka and Its Significance

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Abstract

The environmental evolution of the Mu Us Sandy Land is highly sensitive to global climate change, with its eolian sand-paleosol sequences predominantly influenced by the East Asian monsoon circulation system. However, the response of sandy land evolution to monsoon variations exhibits nonlinear characteristics in local regions, leading to uncertainties in reconstructing regional climate and environmental changes from eolian deposit records. This study employs optically stimulated luminescence (OSL) dating techniques to systematically analyze eight eolian sediment samples from three profiles in the Mu Us Sandy Land. The results indicate: (1) Eolian sand layers were deposited primarily at approximately 12.6 ka and 0.1 ka, corresponding to relatively cold and dry climatic conditions, whereas paleosol layers developed mainly at approximately 6.9 ka and between 9.6–4.2 ka, corresponding to the warm and humid climate of the Holocene Climatic Optimum, revealing that sandy land deposition is influenced by climate change. (2) At approximately 12.6 ka, typical eolian sand layers developed in the southeastern profile of the sandy land, while contemporaneous central region profiles showed no such deposition record, possibly related to wind strength variations induced by regional topographic gradients and local geomorphological differences. (3) The similarities and differences in the initiation and cessation times of paleosol development in interior profiles may be attributed to local ecological processes, topography, and climatic events. (4) The absence of middle to late Holocene deposits in the southeastern profile may be related to regional fluvial erosion, whereas the relatively young eolian sand layer deposited in the upper part of the central region profile may be associated with enhanced eolian activity due to recent regional aridification.

Keywords: OSL dating; eolian deposition; influencing factors; Mu Us Sandy Land

1.1 Study Area Overview

The Mu Us Sandy Land (37.5°-39.5°N, 107.4°-110.5°E), covering an area of 31,260 km^2, is the largest of China’ s four major sandy lands. The terrain generally slopes from northwest to southeast, with elevations ranging from 1,000 to 1,400 m. The northwestern tablelands reach up to 1,600 m, while the southeastern river valley areas are around 1,000 m. The eastern region has a relatively well-developed drainage system dominated by exorheic rivers such as the Wuding and Kuye rivers, which exhibit high runoff variability, whereas the interior features mostly seasonal endorheic rivers. The sandy land is characterized by interspersed mobile dunes, fixed and semi-fixed dunes, and farmland, primarily in the form of barchan dunes and dune chains. The western region typically develops desertified steppe landscapes dominated by eolian sand and exposed bedrock, while the southeastern region has thicker eolian deposits with visible bedrock outcrops due to fluvial erosion. Previous studies indicate that the bedrock consists mainly of red sandstone.

The Mu Us Sandy Land experiences a temperate arid to semi-arid continental climate, with warm and humid summers influenced by monsoons and cold, dry winters dominated by the Siberian high-pressure anticyclonic wind system. Mean annual temperatures range from 6.0-9.0°C, and annual precipitation ranges from 250-440 mm, concentrated primarily in summer. Station records show that wind speeds exceeding 5 $\mathrm{m \cdot s^{-1}}$ account for 12%-20% of observations, with the strongest winds occurring in spring.

1.2 Sample Collection and Preprocessing

Based on field investigations in the Mu Us Sandy Land, two detailed expeditions were conducted to collect samples from three typical eolian deposition profiles. For comparative analysis of topographic influences on deposition processes, two profiles (WSQ-N and WSQ-S) were selected in the central region near Uxin Banner town, sharing similar climatic conditions, flat terrain, and comparable dune orientations. Profile WSQ-N (38°38 14 N, 108°47 8 E) represents a typical sandy land environment in the northern area, while profile WSQ-S (38°33 57 N, 108°54 5 E) is located in a relatively low-lying area southeast of the town where lakes and marshes are well developed, forming a micro-geomorphological contrast with WSQ-N. The third profile (GJG; 37°33 20 N, 109°11 40 E) was selected in the southeastern marginal area, where significant topographic relief and dense seasonal gully systems create typical erosional landforms that may have experienced depositional hiatuses due to fluvial erosion.

Before sampling, fresh profiles were cleaned and described, focusing on key stratigraphic boundaries such as the top and bottom of dark black sandy paleosols and contacts between different eolian facies. Samples were collected by horizontally inserting 5-cm-diameter stainless steel tubes into target strata, sealing both ends with black plastic bags to prevent light exposure. After extraction, tubes were labeled and prepared for laboratory processing. Samples were collected from the WSQ-N and WSQ-S profiles at depths of 0–230 cm and 0–300 cm, respectively, with particular attention to the paleosol layer. At the naturally exposed WSQ-S profile, samples were collected at the interface between paleosol and eolian sand layers.

Laboratory preprocessing was conducted under dim red light. After opening the tubes, potentially exposed material from the tube ends was collected for moisture content and elemental analysis. The remaining material was washed and treated with 10% HCl and 30% H_2O_2 to remove carbonates and organic matter, respectively. Samples were then rinsed, oven-dried, and sieved to isolate the 90–125 μm grain size fraction. Quartz grains were separated using sodium polytungstate heavy liquids with densities of 2.58, 2.62, and 2.75 $g \cdot cm^{-3}$, then etched with 40% HF for 40 minutes to remove feldspar impurities and alpha-irradiated outer layers. Finally, grains were washed with 10% HCl and distilled water, then dried at room temperature for instrumental analysis.

1.3 OSL Dating Analysis

Equivalent dose measurements were performed primarily on a Risø TL/OSL-DA-20 luminescence reader at Jiaying University, equipped with a $^{90}Sr/^{90}Y$ beta radiation source and blue LED stimulation (470 nm). Infrared stimulation (830 nm) was used to test for feldspar contamination. The single-aliquot regenerative-dose (SAR) protocol was employed for all samples using the small-aliquot method, with aliquot diameters of approximately 2 mm and 24–48 aliquots measured per sample.

Annual dose rates were calculated based on radioactive element concentrations (U, Th, K) in the burial environment, cosmic ray contribution, and water content. U and Th concentrations were measured by inductively coupled plasma-mass spectrometry (ICP-MS), and K by inductively coupled plasma-atomic emission spectrometry (ICP-AES). Cosmic ray dose rates were calculated based on latitude, longitude, elevation, and burial depth. Water content was estimated at 5% ± 0.05% based on field measurements.

To verify quartz purity and SAR protocol suitability, sample WSQ-N-2 was selected for preheat plateau and dose recovery tests. Preheat temperatures ranging from 180°C to 280°C at 20°C intervals were evaluated, with three aliquots per temperature. Results showed stable equivalent dose values across temperatures, with 240°C selected as the standard preheat temperature. Dose recovery tests yielded measured/given dose ratios of 1.0 ± 0.1, confirming protocol reliability. All samples exhibited strong OSL signals dominated by the fast component, with dose-response curves passing near the origin and natural doses falling within the reliable range of the response curve.

2.1 Dating Results

Systematic OSL dating of eight eolian sand-paleosol sequence samples from three profiles yielded reliable chronological data. All profiles showed stratigraphically consistent age sequences, with ages decreasing upward [Figure 4: see original paper]. The WSQ-N profile consists of a basal red sandstone layer, middle dark black sandy paleosol layer (9.6–4.3 ka), and upper gray-yellow eolian sand layer (0.1 ka). OSL results reveal an unconformity between the paleosol and underlying red sandstone, indicating missing deposits older than 9.6 ka, and a depositional hiatus between the upper sand and paleosol layers.

The WSQ-S profile comprises a thin basal eolian sand layer (12.6 ka), middle dark black sandy paleosol layer (8.6–4.2 ka), and upper young gray-yellow eolian sand layer. Field observations and OSL dating suggest a depositional hiatus of approximately 4.2 ka between the paleosol and the overlying loose sand layer that was difficult to sample in situ. The GJG profile consists of a basal gray-yellow eolian sand layer (12.6 ka) and upper paleosol layer (6.9–5.7 ka), revealing a depositional hiatus of about 5.7 ka between them.

2.2 Evolution History of Eolian Sand since 12.6 ka

The eolian sand-paleosol sequences in the Mu Us Sandy Land record regional paleoclimatic and paleoenvironmental changes since the Late Quaternary. Generally, eolian sand layers deposited during cold, dry periods indicate active eolian activity, whereas paleosols developed during warm, humid periods indicate dune stabilization and weak eolian activity. The gray-yellow eolian sand layer in the study profiles, dated to 12.6 ka, represents the oldest depositional unit from the last deglaciation period. Comprehensive paleoclimatic proxy analysis indicates low annual precipitation and overall cold-dry conditions during this period, consistent with low solar radiation values and low magnetic susceptibility records from adjacent profiles, all supporting a cold-dry regional climate. Although wind strength decreased compared to the Last Glacial Maximum and dune mobility began to weaken, the Mu Us Sandy Land likely remained dominated by active sand, with eolian activity still vigorous across most areas. This cold-dry climate limited vegetation growth and prevented paleosol development, while sand layer accumulation indicates strong regional eolian activity.

The dark black sandy paleosol layer in the WSQ-N profile dates to 9.6–4.3 ka, spanning the Holocene Climatic Optimum. Paleoclimatic proxies show increased regional precipitation during this period, consistent with high solar radiation values and high magnetic susceptibility records, indicating warm-humid conditions, good vegetation growth, significant dune fixation, and substantially reduced eolian activity. The WSQ-N and WSQ-S profiles both show that paleosol development ceased at approximately 4.2–4.3 ka following the Holocene Climatic Optimum, possibly indicating an important climate transition event characterized by accelerated aridification and rapid expansion of surface desertification. Recent studies indicate that the monsoon rain belt in northern China shifted southward at approximately 4.2 ka, and concurrent arid hydroclimatic conditions may have prevented further paleosol development.

Both the WSQ-N and WSQ-S profiles developed thick, loose eolian sand layers in their upper sections with relatively young formation ages. Notably, the WSQ-N sand layer dates to 0.1 ka, consistent with surface sand layers in adjacent Tukexian profiles. Studies from typical profiles in the eastern and southeastern Mu Us Sandy Land also show significantly enhanced eolian activity over the past century, as indicated by low magnetic susceptibility values in sediments, revealing intensified eolian activity and regional climate aridification. As a material transport transition zone between the Loess Plateau and desert systems, the Mu Us Sandy Land experiences continuous reworking of surface eolian deposits during periods of strong eolian activity, resulting in younger depositional ages and greater accumulation thickness in upper sand layers.

2.3 Factors Influencing Eolian Deposition in the Mu Us Sandy Land

Comparative analysis of the southeastern GJG profile and central region profiles reveals spatiotemporal heterogeneity in eolian deposition. During 12.6–6.9 ka, the southeastern area deposited typical eolian sand layers, while the interior region lacks such records, possibly because the southeastern area functions as a sand accumulation zone whereas the interior acts as a sand erosion zone due to geomorphological differences. The depositional record discrepancy may stem from coupling between regional geomorphological patterns and eolian dynamics. The Mu Us Sandy Land exhibits higher topography in the northwest and lower in the southeast, with the southeastern area forming a regional sand accumulation zone due to blocking by the Baiyu Mountains, while the northwestern area serves as the primary sand source zone under wind erosion. This geomorphological differentiation results in the southeastern region receiving long-term ancient eolian deposition and preserving older stratigraphic sequences, whereas the interior and northwestern regions may retain only Holocene "fragments" of alternating paleosols and eolian sand due to wind erosion.

The GJG profile lacks deposits since 6.9 ka, likely related to fluvial erosion due to its higher topographic position. During the humid Holocene Climatic Optimum, the nearby Salawusu River valley may have accumulated extensive fluvio-lacustrine deposits in low-lying areas, while the elevated GJG profile became a preferential erosion zone for surface runoff. This topography-driven sedimentation-erosion pattern demonstrates that regional stratigraphic hiatuses are related not only to climate fluctuations but also to regional geomorphological evolution. The study results indicate that the spatiotemporal heterogeneity of eolian sequences in the Mu Us Sandy Land may be influenced by combined climate and geomorphological processes.

During 9.6–4.2 ka, dark black sandy paleosols were widely developed across study profiles, consistent with the warm-humid Holocene Climatic Optimum. Notably, despite the close proximity (~15 km) of WSQ-N and WSQ-S profiles and their highly consistent regional climate background (wind direction, effective precipitation, drought frequency) and similar dune characteristics (orientation, morphology), significant differences exist in paleosol development timing: WSQ-N initiated at ~9.6 ka while WSQ-S began at ~8.6 ka. This developmental asynchrony may be related to local hydrological processes. For example, WSQ-N is at higher elevation (1,341 m), while WSQ-S is surrounded by extensive depressions and lake-basin systems that may have delayed paleosol initiation in the early-mid Holocene through local water convergence, causing nonlinear responses of interior eolian deposition to climate change. Both profiles ceased paleosol development at ~4.2–4.3 ka, likely related to drought events caused by southward monsoon rain belt migration after the Middle-Late Holocene, revealing the controlling influence of regional climate abrupt changes on eolian deposition.

Although WSQ-S is situated in a depression that may have experienced more intense surface water retreat during aridification, while WSQ-N was mainly affected by atmospheric precipitation reduction, both ultimately exceeded pedogenic thresholds, resulting in paleosol cessation. In the Late Holocene, both profiles developed loose eolian sand layers that covered the paleosols, representing a positive feedback response of the eolian system to aridification. This "stratigraphic rejuvenation" phenomenon indicates that sandy land deposition is both uniformly regulated by regional climate change and influenced by local topographic and hydrological differences. This pattern provides important reference value for understanding environmental change information at different timescales preserved in eolian deposits.

3 Conclusions

Based on OSL dating and sedimentary characteristic analysis of eight eolian samples from three typical profiles in the Mu Us Sandy Land, combined with chronological sequences, sedimentary facies changes, and regional geomorphological comparisons, the following conclusions are drawn:

1. **Climate-driven impacts**: Eolian sand layers deposited at ~12.6 ka and ~0.1 ka, while paleosol layers developed at ~6.9 ka and 9.6–4.2 ka, corresponding to cold-dry climates and the warm-humid Holocene Climatic Optimum, respectively. This confirms that dune evolution in the region is influenced by climate change, with dune activation under cold-dry conditions and stabilization under warm-humid conditions.

2. **Geomorphological influences**: At ~12.6 ka, the southeastern profile deposited eolian sand layers while interior profiles lacked such deposition, possibly due to regional geomorphological differences that make the southeastern area a sand accumulation zone and the interior an erosion zone. The absence of deposits since 6.9 ka in the southeastern GJG profile may be related to fluvial erosion due to its high topographic position.

3. **Multi-factor synergistic effects**: The similarities and differences in paleosol initiation and cessation times in interior profiles may be influenced by comprehensive factors including local ecological processes, topography, and climatic events. The spatiotemporal heterogeneity of eolian sequences results from combined climate and geomorphological processes.

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