Preliminary Study on Grain Size Characteristics of Sediments in Dunhuang Yardang Strata (Postprint)

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Abstract

Yardang strata constitute the material manifestation of the entire depositional system that existed prior to Yardang landform development, recording substantial information about depositional processes, while sediment analysis serves as the foundation for interpreting this critical information. This study takes the Yardang landforms of Dunhuang as its research subject and conducts a preliminary investigation of the grain-size characteristics of sediments from exposed strata. The results demonstrate that: (1) The grain-size composition of sediments in the Dunhuang Yardang strata is dominated by silt, with average contents of 41.08% (YA), 36.82% (YB), and 35.41% (YC), showing a decreasing trend from east to west, and contains a relatively high proportion of coarse sand components whose spatial variation trend is opposite to that of silt. (2) The vertical variation characteristics of grain-size composition and grain-size parameters in the Yardang strata sediments are pronounced; depositional segments in the profile exhibit cyclical variations between coarse-grained (primarily medium and fine sand) and fine-grained (primarily silt and clay) materials, with interfaces corresponding to the three-tiered structure of the Yardangs. (3) Yardang strata represent the product of mixed accumulation of diverse sediments formed under varying depositional environments and dynamic mechanisms, primarily resulting from alternating deposition in aeolian, fluvial, and lacustrine environments; the sub-environment types within fluvial and lacustrine depositional environments are particularly complex and diverse, warranting further in-depth investigation.

Full Text

Preamble

Grain-Size Characteristics of Yardang Strata Sediments in Dunhuang: A Preliminary Study

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Abstract: The yardang strata represent the material manifestation of the entire depositional system prior to yardang landform development, preserving substantial information about sedimentary processes. Sediment analysis serves as the foundation for interpreting this key information. This study investigates the grain-size characteristics of exposed strata in the Dunhuang yardang landforms. The results indicate: (1) The grain-size composition of Dunhuang yardang strata is dominated by silt, with average contents of 41.08%, 36.82%, and 35.41% respectively, decreasing from east to west. The strata also contain substantial coarse sand components, showing a spatial trend opposite to that of silt. (2) Vertical variation in grain-size composition and parameters is pronounced, with profile sediments characterized by cyclic alternation between coarse fractions (primarily medium and fine sand) and fine fractions (primarily silt and clay). The interfaces between these cycles correspond with the three-tiered 阶梯 morphology of the yardangs. (3) The yardang strata result from mixed accumulation of various sediments formed under different depositional environments and dynamic mechanisms, primarily representing alternating aeolian, fluvial, and lacustrine deposition. The sub-environmental types within fluvial and lacustrine settings are particularly complex and diverse, warranting further intensive research.

Keywords: yardang strata; sediment; grain-size analysis; grain-size frequency distribution curve; grain-size parameters

Grain-size composition represents one of the most widely distributed sedimentary characteristics, controlled by transport medium, transport mode, and depositional environment, thereby producing different grain-size assemblages and distribution patterns. Sediment grain-size composition can reflect not only depositional environment characteristics but also the intensity of surface dynamic processes. Consequently, grain-size analysis, as a fundamental standard parameter for determining depositional environment, dynamic mechanisms, and development processes, has been widely applied in aeolian geomorphology research and proven effective, though its application in yardang geomorphology remains limited.

Yardang strata, or yardang sedimentary layers, refer to layered rocks formed during different geological periods, here mainly representing surface manifestations of stratigraphic accumulations with distinct sequential structures. These strata comprise varying numbers of sedimentary layers with significant thickness variations, characterized by alternating hard, cemented aqueous deposits and soft aeolian accumulations. Currently, research on yardang strata remains primarily qualitative, focusing mainly on interpretation of sedimentary facies and environments, necessitating more intensive quantitative investigation. The Dunhuang yardang landforms are large-scale, relatively concentrated, and exhibit clear sequential structural characteristics, with a thick (approximately 80 cm) alluvial Gobi gravel layer commonly capping their surfaces, representing the final depositional layer prior to yardang erosion initiation. Thus, they preserve complete stratigraphic sequences, making them ideal for yardang sedimentary strata research. While scholars have conducted preliminary studies on geochemical elements and heavy mineral composition of Dunhuang yardang strata sediments, research on grain-size distribution characteristics remains insufficient.

Based on field investigation and experimental analysis, this paper focuses on analyzing the grain-size composition characteristics of yardang strata sediments, discussing their spatial variability and depositional environment types, thereby providing fundamental data for analyzing yardang strata formation, evolution, and dynamic conditions.

1 Study Area Overview

Dunhuang Yardang World Geopark (hereafter "Yardang Geopark") is located at the western end of the Hexi Corridor, approximately 160 km northwest of Dunhuang City, on the western margin of the Dunhuang Basin, at geographic coordinates 40°25 36 ~40°33 10 N, 90°00 00 ~93°13 30 E. Administratively, it lies at the Xinjiang-Gansu border. The park extends approximately 13 km east-west with a total area of 346.34 km^2. The eastern and northern margins connect closely with the alluvial-proluvial inclined plain at the front of the North Mountains; the southern boundary adjoins the Dunhuang Xihu National Nature Reserve (hereafter "Xihu Wetland"), known historically as Halaqi Lake, the terminal point of the Shule River, whose ancient channel traverses the wetland from east to southwest, approximately 20 km from the geopark. The southwest region borders the Kumtagh Desert, where yardang landforms overlap with the eastern desert area; the western and northwestern margins are adjacent to the Aqik Valley and the nearly north-south trending Sanlongsha.

The geopark is situated deep within the Eurasian continent, far from oceans, characterized by a typical warm temperate extreme arid climate with aridity index exceeding 14.99. The climate is dry with scarce precipitation (annual average 11.5 mm) and large interannual variability, high potential evaporation, abundant sunlight, intense solar radiation, large seasonal and diurnal temperature variations (annual average temperature 11.5°C), short frost-free periods, frequent high-wind days (annual average wind speed 3.11 $m \cdot s^{-1}$), and active dust storm activity (meteorological data from Ruoqiang County).

2.1 Sample Collection

To reflect spatial variability in yardang strata sediment grain-size characteristics, we selected three complete yardang profiles at the same latitude from east to west as sampling targets, designated as profiles YA, YB, and YC. Each profile comprises two parts: the aboveground yardang body and the adjacent mechanically excavated underground sediment layer.

Profile YA (40°29 26.83 N, 93°14 29.63 E) measures approximately 902 m in length, 117 m in width, and 35 m in height, exhibiting three-tiered 阶梯 morphology with interfaces at approximately 5.14 m and 7.20 m. Profile YB (40°29 50.59 N, 93°09 24.92 E) measures approximately 843 m in length, 107 m in width, and 31 m in height, also showing three-tiered 阶梯 morphology with interfaces at approximately 7.21 m and 11.58 m. Profile YC (40°30 5.14 N, 93°00 24.84 E) measures approximately 816 m in length, 105 m in width, and 29 m in height, with three-tiered 阶梯 morphology and interfaces at approximately 9.16 m and 13.81 m.

Following the principle of sampling layer by layer from top to bottom, we collected 5-7 samples from different positions within each layer, then uniformly mixed them to obtain representative samples for each yardang stratum. Using this method, we collected 49 samples total, which after mixing and extraction yielded 14 representative yardang sediment samples.

2.2 Testing and Analysis

Sediment grain-size testing was completed at the Key Laboratory of Western China' s Environmental System, Lanzhou University. Sample pretreatment followed methods used in previous research. First, 10 mL of hydrogen peroxide was added to beakers containing 1.5 g of original sample to remove organic matter. The beakers were then heated on a hot plate in a fume hood until the solution clarified and no fine bubbles remained. Next, 10 mL of hydrochloric acid solution was added and heated for approximately 10 minutes to remove carbonates. After treatment, the sample solution was filled with distilled water and left to stand for 24 hours. Following settling, the supernatant was removed, 10 mL of 0.05 $g \cdot L^{-1}$ sodium hexametaphosphate ($(NaPO_3)_6$) was added, and the sample was placed in an ultrasonic cleaner and shaken for approximately 10 minutes. Finally, samples were transferred to a laser particle size analyzer for measurement in volume percentage. Each sample was measured three times and averaged, with measurement errors typically less than 3%.

Equipment included a Mastersizer 2000 laser particle size analyzer, Hydro 2000G wet dispersion system, neon gas laser light source (0.632 m), and blue auxiliary light source (0.466 m), with a measurement range of 0.02–2000 m and 52 size classes.

Mathematical statistical methods were introduced for grain-size data analysis. Folk and Ward parameters were calculated to intuitively reflect sediment grain-size distribution patterns:

Mean grain size (M) = $(\phi_{16} + \phi_{50} + \phi_{84})/3$
Sorting coefficient (δ) = $(\phi_{84} - \phi_{16})/4 + (\phi_{95} - \phi_{5})/6.6$
Skewness (Sk) = $(\phi_{16} + \phi_{84} - 2\phi_{50})/2(\phi_{84} - \phi_{16})$
Kurtosis (Kg) = $(\phi_{95} - \phi_{5})/2.44(\phi_{75} - \phi_{25})$

where ϕ_{16}, ϕ_{25}, ϕ_{50}, ϕ_{75}, ϕ_{84}, ϕ_{95}, and ϕ_{95} represent the corresponding percentiles of the grain-size distribution.

3.1 Grain-Size Composition

The grain-size composition distribution characteristics are shown in Figure 3. Statistical analysis reveals that Dunhuang yardang strata sediments are dominated by silt, with average contents of 41.08% (profile YA), 36.82% (profile YB), and 35.41% (profile YC), decreasing from east to west. This spatial differentiation is significant. Coarse sand content is generally low but notably higher in profile YA, averaging 9.98%—far exceeding other profiles. The spatial variation trend is opposite to that of silt.

Clay, as the finest sediment component, represents suspended load associated with loess and dust storms or distal suspended load in lacustrine sediments. Field investigations show that clay layers in the profiles are well-cemented, hard-textured, and exceed 50 cm in thickness, potentially serving as an effective proxy for quiet-water deposition in lake centers. Clay content in profile YA is higher than in other profiles, averaging 18.33%, while profiles YB and YC are similar at 14.69% and 12.13% respectively. In terms of relative proportions among grain-size fractions, profile YA shows the sequence: silt > clay > fine sand > medium sand > coarse sand. Profiles YB and YC are similar: silt > clay > fine sand > medium sand > coarse sand. Profile YA shows greater variability: silt > clay > coarse sand > medium sand > fine sand. Additionally, according to the Wentworth scale, silt can be further subdivided into coarse silt, medium silt, fine silt, and very fine silt. Normalized statistical analysis of silt components across all profiles (Figure 3) shows that profiles YA and YB are similar, with increasing content from coarse silt to very fine silt, while profile YC shows the opposite trend.

These findings differ substantially from previous studies of yardang sediments in the Chaerhan Salt Lake and Bailongdui areas. Although all are silt-dominated, Chaerhan Salt Lake and Lop Nur yardangs contain 69.26% and 80.05% silt respectively, occupying absolutely dominant positions, and Chaerhan Salt Lake yardangs contain no coarse sand. This discrepancy likely relates to Dunhuang yardangs' more complex and diverse transport-deposition processes.

Beyond spatial differences, vertical variation in different grain-size fractions within yardang strata is also significant. Figure 4 shows the distribution curves of different grain-size fractions with height in profile YA. Based on curve fluctuations, profile YA can be divided into three depositional segments: segment YA29–YA49 is dominated by silt and clay with average contents of 47.46% and 18.56% respectively, with other components low or absent; segment YA17–YA28 is dominated by medium and fine sand with average contents of 34.13% and 28.84%, while very fine sand, silt, and clay show minor peaks of 37.40%, 7.21%, and 25.47% respectively; segment YA01–YA09 is dominated by silt and clay with average contents of 68.24% and 13.81%, with coarse, medium, and fine sand nearly absent and very fine sand fluctuating between 0.17% and 8.33%. The interfaces between these three segments correspond well with the three-tiered 阶梯 morphology interfaces at approximately 5.14 m and 7.20 m, suggesting a genetic relationship.

Similarly, profiles YB and YC show fluctuating curves of grain-size content with height (Figure 5). Based on curve characteristics, especially for medium sand, fine sand, silt, and clay, profile YB can be divided into three depositional segments: segment YB19–YB28 is dominated by silt and clay with average contents of 63.22% and 22.20%; segment YB10–YB16 is dominated by medium and fine sand with average contents of 27.98% and 36.47%; segment YB01–YB09 is dominated by silt and clay with average contents of 45.77% and 16.56%. Although cyclic characteristics are less pronounced in profile YC, segment interfaces still correspond well with three-tiered 阶梯 morphology interfaces.

Some scholars have interpreted the three-tiered yardang morphology as three-level river terraces formed by tectonic uplift. However, this analysis shows that depositional segment interfaces correspond well with three-tiered 阶梯 morphology interfaces, suggesting that differential erosion between depositional segments may be an important factor controlling three-tiered morphology development.

3.2 Grain-Size Frequency Distribution Curves

Frequency curves provide intuitive visual representation of sediment grain-size distribution. Due to differences in material properties and transporting agents, sediment particles undergo varying degrees of creep, saltation, and suspension, forming different frequency curves. In other words, grain-size distribution characteristics differ significantly among various depositional environments.

Figure 6 shows yardang strata sediment grain-size distribution curves, with mixed and overlapping curves among profiles reflecting inter-sample differences. In profile YA samples, peaks range 3–450 m, with good continuity indicating diverse sediment types. Curve morphology is dominated by unimodal forms, including narrow unimodal (peaks ~100–450 m, coarser material) and smooth unimodal (peaks ~5-50 m, finer material), plus minor bimodal curves with indistinct secondary peaks.

Profile YB samples show similar characteristics, with narrow and smooth unimodal peaks ranging 10-300 m, though continuity is lacking near 10 m. Profile YC samples show more chaotic frequency curves, with peaks concentrated in three ranges (3-7 m, 200-600 m, and 3-600 m) and poorer continuity. Curve morphology includes narrow unimodal, smooth unimodal, and asymmetric bimodal forms, with smooth unimodal peaks focusing around 5-50 m and narrow unimodal and asymmetric bimodal curves overlapping at larger grain sizes.

3.3 Grain-Size Parameters

Mathematical statistical analysis yields grain-size parameters for yardang profiles (Table 2). Overall mean grain-size values are similar among profiles, except profile YA which has higher coarse sand content with a mean of 126.90 m. Sorting coefficient reflects grain-size dispersion—smaller values indicate more concentrated distributions. According to Folk and Ward classification standards, average sorting coefficients range 1.38-1.45, indicating poor sorting. Skewness and kurtosis reflect symmetry and peakedness of frequency curves. Average skewness ranges 0.24-0.28 (positive skew), and average kurtosis values are 0.75-1.00 (very narrow). Thus, average parameters are similar among profiles with limited spatial differentiation, but individual samples show significant variability: sorting coefficients range 0.64-2.64 (spanning good to very poor sorting); skewness varies -0.23 to 0.71 (negative skew to near-symmetric to positive to strongly positive); kurtosis ranges 0.75-14.00 (from broad to narrow to very narrow), showing diverse curve shapes.

Based on these inter-sample differences, we analyzed vertical variation of grain-size parameter values with height (Figure 4, 5). According to parameter curve fluctuations, yardang strata can be consolidated into three depositional segments, consistent with divisions based on different grain-size fraction content curves.

3.4 Sedimentary Environment Analysis

Grain-size composition analysis shows that yardang sediments are silt-dominated, with substantial medium sand, fine sand, and clay components, and exhibit clear coarse (medium/fine sand) and fine (silt/clay) cyclic variation. During transport, silt and clay as suspended load typically indicate lacustrine environments; fine sand represents near-source aeolian or fluvial transport, indicating aeolian and fluvial deposition; medium sand is primarily associated with surface alluvial processes. Therefore, we selected coarse (medium + fine sand, 125-500 m) and fine (silt + clay, <62.5 m) environmentally sensitive fractions as indicators for depositional environment discrimination.

As shown in Figure 7, yardang sediment scatter points show clear clustering, divisible into three groups representing three depositional environment types, designated Cluster 1, Cluster 2, and Cluster 3. Based on environmental significance of different grain-size fractions: Cluster 1 has lower silt+clay content (<50%) and higher medium+fine sand content, possibly representing aeolian or alluvial environments; Cluster 3 has higher silt+clay content (>70%) and lower medium+fine sand content (<20%), possibly representing lacustrine environments; Cluster 2 falls between these, making identification difficult based solely on sensitive components.

Comparative analysis with known depositional environment sediments provides another effective method. Research shows that different depositional environments exhibit distinct frequency curve morphology and peak characteristics. Fluvial sediments typically comprise coarse and fine components—Tarim River, Heihe River, and Shiyang River sediments peak at 80–400 m; aeolian sediments show unimodal distribution with excellent sorting, with Badain Jaran and Horqin sandy lands peaking at 300 m and Kumtagh Desert aeolian sand peaking around 500 m; lacustrine sediments show complex curve types with poor sorting, but exhibit consistent trends from shore to lake center—peaks decreasing from 70–100 m (shore) to 10–70 m (transitional) to 2–10 m (center).

Examining sample frequency curves: Cluster 1 shows extremely narrow unimodal peaks at 120–500 m, with some fine tails, showing high similarity to desert materials and fluvial sediments. Cluster 2 shows asymmetric bimodal morphology with main peaks at 80–300 m and weak secondary peaks at 3–7 m, indicating typical fluvial sediments. In arid regions, weathered dry riverbed sediments show great similarity to desert materials in grain-size distribution but can be distinguished by higher fine material content and poorer sorting. Cluster 3 shows smooth unimodal peaks at 2–60 m with significant continuity, indicating lacustrine sediments.

Thus, yardang strata depositional environments are complex and diverse, not simply alternating fluvial-lacustrine sequences, but exhibiting typical aeolian, fluvial, and lacustrine environments with particularly complex and diverse sub-environmental types in fluvial and lacustrine settings, requiring further intensive research.

Grain-size parameter scatter plots can reflect depositional characteristic differences and represent environments. Using yardang strata sample data, average grain-size shows no significant correlation with sorting coefficient or kurtosis, but weak correlation with skewness. In distinguishing different components, Cluster 1 and Cluster 3 samples show significant differences with clear clustering, while Cluster 2 shows high dispersion in sorting coefficient and kurtosis but good aggregation in skewness. Therefore, grain-size parameters serve as effective indicators for yardang depositional environment discrimination, particularly average grain-size versus skewness scatter plots (Figure 8), which also reveal sub-environmental classification features within Cluster 3.

4 Conclusions

Based on grain-size composition, frequency distribution curves, and parameter analysis, combined with environmentally sensitive component extraction, environmental identification, and parameter validation, this study quantitatively interprets the grain-size characteristics and depositional environment implications of Dunhuang yardang strata sediments:

(1) Dunhuang yardang strata sediments are silt-dominated, with average contents of 41.08% (YA), 36.82% (YB), and 35.41% (YC), decreasing from east to west. The strata contain substantial coarse sand components with spatial trends opposite to silt, differing from previous studies of Chaerhan Salt Lake, Lop Nur, and Aqik Valley yardangs, likely due to Dunhuang yardangs' more complex and diverse transport-deposition processes.

(2) Vertical variation curves of grain-size composition and parameters show that profile sediments are characterized by cyclic alternation between coarse (medium/fine sand) and fine (silt/clay) fractions, reflecting changes in formative processes and development stages. The interfaces between these two cycles correspond with yardang three-tiered 阶梯 morphology interfaces, suggesting that cyclic depositional sequences may be the fundamental cause of yardang 阶梯 morphology development, with subsequent differential erosion being the controlling factor.

(3) Yardang strata result from mixed accumulation of various sediments formed under different depositional environments and dynamic mechanisms, primarily through alternating aeolian, fluvial, and lacustrine deposition. Fluvial and lacustrine sub-environmental types are particularly complex and diverse, requiring further intensive research. These results validate the reliability of medium+fine sand content, silt+clay content, mean grain-size, and skewness as effective indicators for yardang depositional environment discrimination, holding important theoretical significance for such studies.

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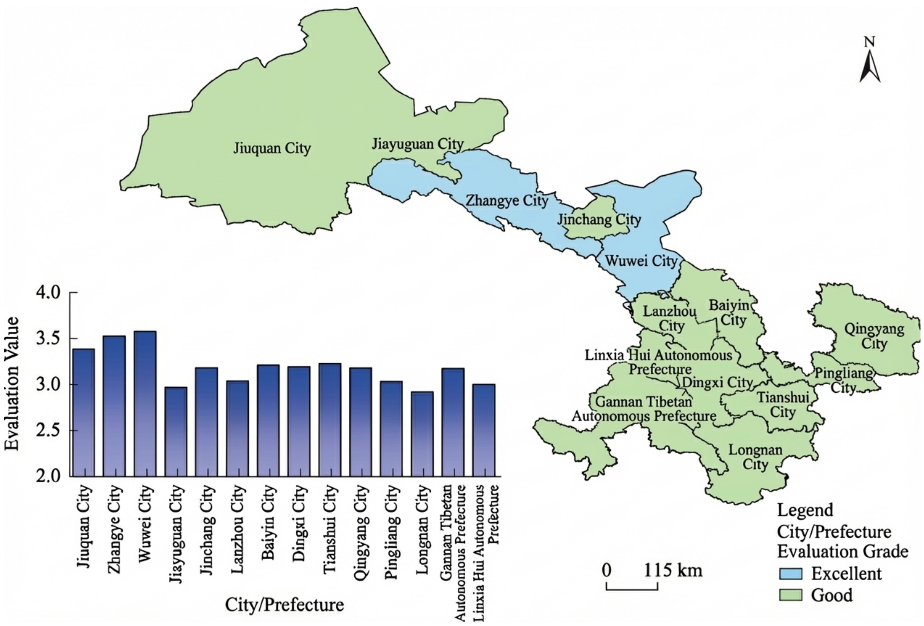

Figure 1: Figure 3

Figures

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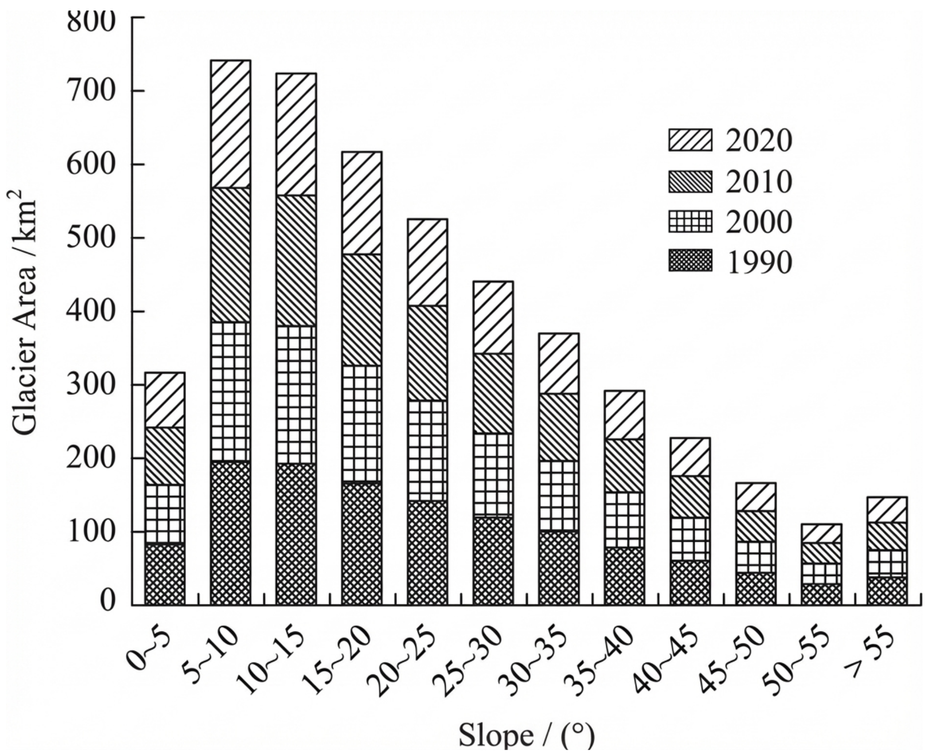

Figure 2: Figure 7