Postprint: Characteristics of Internal Sedimentary Structures of Barchan Dunes on the Southwestern Margin of the Gurbantünggüt Desert

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Date: 2022-06-08T00:00:00+00:00

Abstract

Internal sedimentary structures of sand dunes preserve important information regarding the dynamic evolution processes of dunes. Taking the fixed and semi-fixed crescentic dune area on the southwestern margin of the Gurbantunggut Desert as the study area, ground-penetrating radar was employed during spring and autumn to detect the internal structures of fixed and semi-fixed crescentic dunes, obtaining internal structure image information at depths of approximately 8 m for crescentic dunes of various scales and morphologies. Through image gain processing, interpretation, and comparative analysis, it is revealed that: (1) Fixed and semi-fixed crescentic dunes in the Gurbantunggut Desert exhibit five types of radar facies of internal dune structures, namely high-angle inclined bedding, wedge-shaped cross-bedding, convex-upward cross-bedding, low-angle subhorizontal bedding, and massive bedding, with the first four types primarily distributed in the shallow layer at 3–5 m depth, while massive bedding is mainly distributed below 4–5 m depth. (2) High-angle inclined bedding and wedge-shaped cross-bedding are mainly distributed in the upper windward slopes and crest zones of tall crescentic dunes (chains). The former is formed by the burial of leeward foreset beds, reflecting relatively frequent aeolian activity on the upper windward slopes and crests of tall crescentic dunes; the buried foreset laminae are exposed due to wind erosion after the dunes undergo "body-fixing and crest-shrinking" . The latter represents structures formed by the infilling of wind erosion pits and troughs on windward slopes by aeolian sand flow, or structures created by seasonal wind direction variations at dune crests. (3) The convex-upward cross-bedding associated with shrub-coppice dunes is widely distributed in the middle to lower windward slopes of crescentic dunes, with local occurrences also on leeward slopes, indicating that shrub-coppice dunes occupy an important position in surface aeolian processes of dunes. The deep massive bedding likely results from strong bioturbation of early aeolian deposits, leading

to the destruction of primary bedding. (4) The types and combined distribution characteristics of the aforementioned internal dune structures reflect that crescentic dunes in the study area are generally trending toward a stable or degraded state, which is consistent with the geomorphological change features of modern dunes undergoing "body-fixing and crest-shrinking" . For instance, wind erosion troughs are common on the middle to upper windward slopes and crests, while foreset bed development slows on leeward slopes due to slope gentling, and modern aeolian activity is mainly concentrated on the upper portions and crests of crescentic dunes. Thus, it is evident that the internal structures and their combined distribution characteristics of fixed and semi-fixed crescentic dunes in the study area differ from those of mobile crescentic dunes, and also show certain consistency with regional natural geographic environmental change trends over the past half-century, including warming and wetting climate, decreasing average wind speeds, and increasing vegetation coverage in the deserts of northern Xinjiang.

Full Text

Internal Sedimentary Structure Characteristics of Barchan Dunes in the Southwestern Margin of the Gurbantunggut Desert

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Abstract: The internal sedimentary structure of aeolian dunes preserves important information on the dynamic evolution of dune morphology. This study focuses on fixed and semi-fixed barchan dunes in the southwestern margin of the Gurbantunggut Desert, Xinjiang, China. Using ground-penetrating radar (GPR), we conducted surveys in both spring and autumn to detect the internal structures of these dunes, obtaining high-resolution images of sedimentary architecture at depths of approximately 3–5 m across dunes of varying sizes and morphologies. Through image enhancement processing, interpretation, and comparative analysis, we identified five distinct radar facies: high-angle dipping oblique bedding, wedge cross-bedding, convex cross-bedding, low-angle to sub-horizontal bedding, and massive bedding. The first four types are predominantly distributed in shallow layers at depths of 3–5 m, while massive bedding occurs mainly below 4–5 m. High-angle dipping oblique bedding and wedge cross-bedding are concentrated in the upper windward slope and crest of large barchan dunes (chains). The former represents buried foreset deposits from leeward slopes, indicating frequent aeolian activity on the upper windward slope and crest, where buried foreset laminae become exposed due to wind erosion following dune "fixation and crest reduction." The latter forms through infilling of wind-eroded pits and troughs on windward slopes or through seasonal wind direction variations at the crest. Convex cross-bedding, associated with shrub-coppice dunes, is extensively distributed across the middle and lower windward slopes, with localized occurrences on leeward slopes, demonstrating the significant role of shrub dunes in surface aeolian processes. Deep massive bedding likely results from strong bioturbation of early aeolian deposits, causing the disappearance of primary stratification. The combination and distribution of these internal structures reflect an overall stable or declining state of barchan dunes in the study area, consistent with the geomorphic characteristics of modern dunes undergoing "fixation and crest reduction." For instance, wind erosion troughs are common on the middle-upper windward slopes and crests, while the reduced slope gradient on leeward slopes slows foreset development, concentrating modern aeolian activity on the upper dune and crest regions. These internal structural characteristics of fixed and semi-fixed barchan dunes differ markedly from those of mobile barchan dunes and align with regional environmental changes in northern Xinjiang over the past half-century, including warming and wetting climate trends, decreasing mean wind speeds, and increasing vegetation coverage.

Keywords: ground penetrating radar; Gurbantunggut Desert; fixed and semi-fixed barchan dune; sedimentary structure; environmental significance

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1 Study Area Overview

The Gurbantunggut Desert is located deep in the interior of the Eurasian continent, situated in the central Junggar Basin of Xinjiang, and represents the largest fixed and semi-fixed desert in China. The desert climate is primarily controlled by the mid-latitude westerly circulation, with an annual mean temperature of 5-7°C and annual precipitation of 70-150 mm. Summer precipitation is slightly higher than in autumn and winter, while stable snow cover persists for 100–160 days during winter and spring. Spring snowmelt creates a suspended wet sand layer 50-60 cm deep. These unique climatic conditions make the desert relatively moist, with widespread distribution of shrubs such as *Haloxylon ammodendron* and *Ephedra distachya*, and extensive development of biological soil crusts formed by algae, fungi, and lichens. Only narrow active mobile zones remain near dune crests, distinguishing this desert significantly from others in China.

The dominant wind regime controlling aeolian geomorphology in the Gurbantunggut Desert is the northwesterly wind associated with the westerly circulation. The Mongolian high-pressure system, limited by seasonality and regional constraints, only significantly influences the central and northeastern parts of the desert during winter and spring. Consequently, the overall dune migration direction is from northwest to southeast. The desert exhibits diverse dune types, with linear dunes (longitudinal dune ridges) being the most representative form, accounting for over 80% of the total fixed and semi-fixed dune area. Barchan dunes and barchan dune chains are distributed in the southwestern margin, while honeycomb dune ridges and compound dune ridges occur in the central-southern region.

The Mosuowan area in the southwestern margin of the desert is dominated by barchan dunes, barchan dune chains, and nest-like dunes, with barchan dunes representing the fundamental aeolian landform type. Under the influence of northwesterly winds, the dunes generally trend northwest-southeast. Extensive saline-alkali lands are distributed to the northwest of Mosuowan, creating a sand-deficient environment in the downwind region. The phenomenon of linear dunes coexisting with barchan dunes is common. Over the past 30 years, the crest positions of barchan dunes (chains) have shown little change, while shrub vegetation coverage in interdune areas and on dune surfaces has continued to increase.

Field investigations reveal that the middle and lower windward slopes and interdune areas of the study region are extensively covered by biological soil crusts and shrub vegetation, effectively inhibiting wind erosion and reducing sand surface activity, resulting in overall stable surfaces. The middle and upper windward slopes widely feature superimposed shrub-coppice dunes and wind erosion pits and grooves of varying widths that parallel the longitudinal dune profile, showing clear wind erosion characteristics. Dune crestlines are undulating and sinuous, with mobile zones 5–20 m wide commonly present at dune tops, indicating strong aeolian activity and frequent erosion-deposition processes. The leeward slope surfaces are covered with shrub vegetation, with the middle and lower slopes becoming gentler, suggesting that barchan dunes (chains) are approaching developmental cessation.

2 Methods

GPR surveys were conducted using a pulseEKKO Pro system manufactured by Sensors and Software Inc. The survey employed the common-offset method, with transmitting and receiving antennas positioned parallel to each other and perpendicular to the ground surface. We selected dune profiles with clearly exposed internal structures for experimental detection to evaluate the influence of different technical parameters on the results.

Based on previous research and field conditions, we used the common midpoint method to determine a radar wave velocity of $0.15\ \mathrm{m \cdot ns^{-1}}$, with a time window of 100 ns, pulse voltage of 400 V, and stacking times of 16 as basic parameters, which balanced detection effectiveness and work efficiency, achieving a vertical theoretical resolution of approximately 0.375 m.

First, we compared detection effects using two antenna frequencies: at 100 MHz frequency, the antenna spacing was 1.0 m with a step size of 0.5 m; at 200 MHz frequency, the spacing was 0.5 m with a step size of 0.1 m. Second, we conducted repeat surveys on the same barchan dune in early April (spring) and early October (autumn) to assess potential effects of seasonal moisture variations in sand layers on detection results.

For formal surveys, we selected 8 barchan dunes with varying morphological characteristics and sizes (Fig. 2) to obtain radar image information on internal structure assemblages at different developmental stages. All survey lines were arranged along dune longitudinal profiles, extending from the windward toe to the leeward toe and perpendicular to the dune crest. We used a Trimble R8 GNSS RTK to measure elevation changes along the survey profiles. Post-processing employed EKKO_{View} 2 and EKKO_{View} Deluxe software for topographic correction, digital filtering, and gain adjustment to remove systematic and environmental noise interference. To maintain data integrity and authenticity, only essential processing such as Dewow gain was applied to the raw data. Based on the texture and structure of radar reflections and their cutting relationships, we classified basic radar facies types of dune internal structures. Each radar facies exhibits similar reflection patterns (e.g., geometric morphology, continuity, amplitude intensity), and interpretations were subsequently developed based on aeolian sand layer structure development theory.

3 Results

3.1 Influence of Different Detection Parameter Settings

Comparative analysis of radar images with actual profile structures revealed that the 100 MHz frequency antenna (Fig. 3) provided better results, with an effective detection depth reaching 3-4 m. The radar images showed good consistency with actual profiles for both horizontal and cross-bedding. The 100 MHz frequency displayed more convex cross-bedding and some discontinuous high-angle dipping oblique bedding at 2-3 m depth. The dip directions of high-angle oblique bedding or tabular cross-bedding matched well, accurately reflecting the dune' s internal structure.

The 200 MHz frequency antenna (Fig. 3) had shallower signal penetration, only obtaining clear, more detailed images within 2-3 m depth. However, comparison with 100 MHz results revealed that because the shallow dune layers are significantly affected by bioturbation, the 200 MHz frequency may amplify biological disturbances such as plant root systems and animal burrows, causing interference with imaging of aeolian sedimentary structures.

Field investigations show that the Gurbantunggut Desert has relatively high vegetation coverage, with grass-shrub vegetation and biological soil crusts widely distributed on dune surfaces except along crestlines. Dune profiles contain numerous plant roots, root channels, gray-black thin sandy soil layers, and soil crusts, along with many large gerbil and lizard burrows. These features indicate that primary stratification is significantly affected by bioturbation. Although seasonal moisture variation in dune subsurface layers is substantial in the study area, adjusting gain intensity can reduce the impact of moisture differences on detection results. After applying varying degrees of gain processing using AGC Gain software, no significant resolution differences were observed between spring and autumn profiles, with both achieving effective detection depths of 3–5 m.

3.2 Influence of Seasonal Moisture Variation on Detection Results

Spring detection images (Fig. 4) show clearer and richer stratification in shallow windward slope layers. On the middle-upper windward slope, high-angle dipping oblique bedding and convex cross-bedding are clearly visible, with occasional wedge cross-bedding. On the lower windward slope, some convex cross-bedding and low-angle to sub-horizontal bedding are visible. These differences likely relate to moisture content variations between dune upper-middle portions and interdune/lower dune areas. Previous studies indicate that the Gurbantunggut Desert has the highest subsurface moisture content in spring, with the upper-middle dune subsurface moisture at approximately 2.01%, while interdune and lower dune areas reach 4.00%. Higher moisture content in lower dune areas intensifies freeze-thaw effects, resulting in more horizontal bedding at dune toes. In autumn, subsurface moisture is lower and more uniform across dune positions (0.45%–0.65%), making these differences less pronounced.

Overall, autumn detection images show similar radar facies assemblages to spring images. The upper windward slope is dominated by convex and wedge cross-bedding, with occasional high-angle oblique bedding. The middle-lower windward slope features interspersed convex cross-bedding and high-angle oblique bedding, with the latter dipping consistently with the leeward slope direction. The upper leeward slope is dominated by high-angle oblique bedding with relatively uniform radar facies, while depths below 3–5 m consist of low-angle to sub-horizontal bedding and massive bedding.

3.3 Radar Facies Types and Distribution Characteristics of Dune Internal Structure

Based on comprehensive analysis of experimental detection results and seasonal barchan dune longitudinal profiles, we identified different radar image structures within dunes and classified five basic radar facies: high-angle dipping oblique bedding, convex cross-bedding, wedge cross-bedding, low-angle to sub-horizontal bedding, and massive bedding.

High-angle dipping oblique bedding shows clear, continuous reflections dipping downwind, consistent with leeward slope orientation. These are mostly parallel or sub-parallel, distributed in the middle-upper windward slope with deeper burial in the lower windward slope, reaching maximum depths of 4–5 m. This radar facies represents foreset deposits from superimposed dune slip faces, reflecting active migration processes on the upper windward slope and crest.

Convex cross-bedding shows clear, strong-amplitude, continuous convex-shaped reflections dipping toward both sides, extensively distributed across windward slope positions and locally on leeward slopes, with maximum bedding thickness of approximately 1 m. Based on observations of shrub-coppice dune profiles in the study area, this radar signal structure closely resembles internal structures of shrub dunes. Previous studies found such convex cross-bedding often occurs where vegetation is buried by dunes, and our detection process noted the same phenomenon. Therefore, we interpret this radar facies as buried shrub-coppice dune structures subsequently covered by aeolian sand layers.

Low-angle to sub-horizontal bedding is mainly distributed at windward toes, locally in depressed sections of the middle-upper windward slope, and at leeward toes, genetically belonging to accretionary bedding. Generally occurring within 3–4 m depth, upper reflection surfaces are clear and continuous. However, with increasing depth, this accretionary bedding may be affected by plant root bioturbation, causing primary aeolian stratification to disappear and reflection signals to weaken with poor resolution.

Wedge cross-bedding shows clear reflections with small dip angles, forming wedge shapes that intersect each other, distributed in the middle-upper windward slope, crest, and leeward toe. Wedge cross-bedding developed in shallow windward slopes may form through infilling of wind-eroded pits and troughs between superimposed shrub mounds, intersecting with overlying low-angle to horizontal bedding. Wedge cross-bedding at the crest may originate from seasonal wind direction variations, while at the leeward toe, intersection of low-angle accretionary layers with underlying wind erosion surfaces can also create wedge cross-bedding.

Massive bedding is generally distributed below 4–5 m depth, with no visible base. Radar reflection images show no heterogeneity, indicating no obvious differentiation in composition and structure of the detected objects and showing no fine-layer stratification. The genesis may involve long-term bioturbation of deep aeolian layers by vegetation, causing the disappearance of primary aeolian stratification.

4 Discussion

4.1 Distribution Characteristics of Radar Facies in Each Detection Profile

We established survey lines on barchan dunes of different morphologies and scales to obtain radar images (Fig. 5). Based on the above radar facies classification, we identified the distribution characteristics of shallow structures in each detected dune.

Profile M4 (Fig. 5a) shows a dune height of approximately 2 m without a slip face, with relatively symmetrical, low, and gentle slopes resembling a cake-shaped sand mound. The detection profile is dominated by low-angle to sub-horizontal accretionary bedding, with superimposed small-scale convex cross-bedding and localized high-angle oblique bedding at the crest, showing relatively uniform radar facies types.

Profile M5 (Fig. 5b) shows a dune height of approximately 4 m with a gentle, slightly convex windward slope (15°–20°) and a steeper leeward slope (26°–30°), with an overall concave form and distinct crestline, similar to an incipient barchan dune. The detection profile shows dense convex cross-bedding on the windward slope, with localized high-angle oblique and wedge cross-bedding in the middle-upper portion and crest. The superimposed convex cross-bedding at the crest is relatively thick. Low-angle to sub-horizontal bedding occurs in low-lying concave sections of the windward slope, while shallow layers of the slip face show accretionary bedding parallel to the dune slope.

Profile M6 (Fig. 5c) shows a dune height of approximately 6 m with a distinct slip face. The windward slope is gentle and convex, with wind erosion troughs and pits widely developed in the middle-upper portion. The crestline is distinct, with the upper slip face slope at 28°–35°, but the middle-lower portion has gentler slopes. The dune planform shows typical barchan morphology. The detection profile reveals dense, overlapping convex cross-bedding across the windward slope, with wedge cross-bedding alternating in the middle-upper windward slope and crest. High-angle oblique bedding is distributed in the upper windward slope, crest, and upper slip face, reflecting migration processes of superimposed mobile dunes on the upper windward slope and crest, as well as frequent aeolian accumulation on the upper slip face. Wedge cross-bedding at the crest may also form from seasonal wind direction alternation. Low-angle to sub-horizontal accretionary bedding occurs in local low-lying areas of the windward slope and at the leeward toe.

Profile M7 (Fig. 5d) shows a dune height of approximately 8 m with a blunt, rounded crest and rounded wing morphology, resembling a shield-shaped dune. The detection profile shows high-angle oblique bedding in the upper windward slope and low-angle to sub-horizontal bedding at the leeward toe. Large-scale convex cross-bedding structures up to 2 m thick in the lower windward slope represent a buried large shrub-coppice dune.

In summary, as barchan dunes in the study area mature and increase in scale, massive bedding begins to develop at depth, while shallow internal structures gradually become richer and more regular with dune morphology and dynamic changes, such as increasing convex cross-bedding on windward slopes and developing wedge cross-bedding at crests.

4.2 Comparison Between Mobile and Fixed/Semi-Fixed Barchan Dune Internal Structures

During barchan dune migration, sand particles are continuously transported from windward to leeward slopes, forming tabular cross-bedding that dips consistently with the leeward slope direction. Therefore, the internal structure model of mobile barchan dunes typically shows foreset bedding dipping leeward at angles approximating the dry sand angle of repose (26°–34°), with set boundaries dipping downwind at low angles (2°–6°). As dunes mature and increase in height and scale, both foreset bedding and set boundaries tend toward higher dip angles.

The internal structure types and distribution characteristics in our study area differ significantly from this model. On longitudinal profiles, high-angle oblique bedding is mainly distributed in dune upper portions (windward and leeward slopes) and crests, extending to shallow depths within 4–5 m in large barchan dunes, but occurring less frequently and at shallower depths in small or incipient dunes. Convex cross-bedding is a common type in shallow structures of barchan dunes at various morphological scales and developmental stages. For mobile dunes, generally only leeward slope bedding is preserved, so the presence of windward slope bedding in our study indicates low dune mobility.

Differences in sedimentary structures across dune positions—such as wedge and high-angle oblique bedding in upper windward slopes and crests—suggest greater mobility in upper dune portions, while dense convex cross-bedding on middle-lower windward slopes indicates stabilization, consistent with the "fixation and crest reduction" landscape. Below 4–5 m depth, all detected dunes show low-angle to sub-horizontal bedding and massive bedding with poor resolution, rather than tabular cross-bedding parallel to leeward slopes. Field observations of exposed dune profiles reveal numerous plant roots crossing aeolian bedding within 1–2 m depth, with thin gray-black sandy soil layers, and stratification disappearing below 3–4 m depth, transitioning to massive structures. This demonstrates that high vegetation coverage, deep root systems, and frequent biological activity significantly impact internal sedimentary structures.

4.3 Genesis of Internal Structures in Barchan Dunes (Chains) of the Study Area

The widespread development of convex cross-bedding in shallow barchan dune structures likely relates closely to regional climate trends toward wetter conditions and increased vegetation coverage from extensive sand stabilization and afforestation efforts. Research shows that over the past 50 years, northern Xinjiang has experienced increasing annual precipitation, reduced near-surface mean wind speeds, increased soil moisture, and improved vegetation growth conditions. Concurrently, enhanced desert ecological protection and comprehensive management measures have promoted vegetation recovery and increased coverage. This process has reduced dune area along the western margin of the Gurbantunggut Desert. Expanding shrub vegetation intercepts wind-blown sand, leading to widespread development of shrub-coppice dunes at desert margins and superimposed small-scale shrub dunes on windward slopes of larger dunes, directly affecting surface aeolian erosion-deposition processes on parent barchan dunes.

As surface plant litter increases and decomposition intensifies, biological soil crusts develop extensively, forming weakly cemented aeolian soils that further trap fine-grained sediments and protect buried dunes from wind erosion, preserving the sedimentary structures of buried shrub dunes. Wang et al. found that dune (dune ridge) stability varies significantly from base to crest, with aeolian activity concentrated in middle-upper portions and crests, while lower slopes and interdune areas remain stable. The favorable water-heat configuration in the Gurbantunggut Desert provides favorable conditions for desert vegetation growth, with vegetation—especially ephemeral plants—being the main contributor to surface stabilization. Biological soil crust rhizoids can tightly attach to sand surfaces, further enhancing stability of interdune areas and lower dune slopes. Additionally, on larger-scale barchan dunes, wind speed gradually increases with elevation on windward slopes, reaching maximum speeds at the crest, making aeolian erosion-deposition processes more frequent in middle-upper portions and crests (Fig. 2). Consequently, our detection commonly identified high-angle oblique bedding and wedge cross-bedding in shallow layers of large barchan dune middle-upper portions and crests.

All detection profiles show weakly reflective, low-resolution massive bedding below 4–5 m depth. These bedding types and their assemblage distributions differ from internal structures of mobile barchan dunes. The genesis may relate to a "homogenization" process where strong bioturbation causes the disappearance of primary aeolian stratification. Studies show that *Haloxylon ammodendron* and *Haloxylon persicum* root systems can extend to 5 m depth, with desert plant root activity continuously disturbing and binding aeolian layers while providing favorable habitats for desert animal activity, especially burrowing animals that further mix sand particles across different layers. In other deserts worldwide, researchers have found similar biological impacts on dune internal structures. Bristow et al. found that on vegetated linear dunes in Australia' s Simpson Desert, microorganisms and shrubs captured fine fractions, increased clay content limited GPR penetration, and abundant burrowing biota reset primary internal structures. Our field observations confirm that high vegetation coverage, deep root systems, and frequent biological activity significantly influence internal sedimentary structures in the study area.

5 Conclusions

Based on field aeolian geomorphology investigations, this study selected fixed and semi-fixed barchan dune (chain) distribution areas in the southwestern margin of the Gurbantunggut Desert. We conducted GPR surveys in spring and autumn on barchan dunes of different morphologies, establishing approximately 1,000 m of survey lines across 8 dune samples to obtain sedimentary structure information within 3–5 m depth. Combined with comprehensive analysis of regional physical geography and dune morphological characteristics, we derived preliminary understanding of internal structure characteristics:

1) Based on radar reflection texture assemblages, this detection identified five

internal structure radar facies: high-angle dipping oblique bedding, convex cross-bedding, wedge cross-bedding, low-angle to sub-horizontal bedding, and massive bedding. The first four show clear reflection signals, but their distribution differs from mobile barchan dunes. High-angle oblique and wedge cross-bedding in shallow layers and massive bedding in deep layers show vertical superposition relationships.

2) High-angle dipping oblique bedding and wedge cross-bedding are mainly distributed in the toe, upper portion, and crest of large barchan dunes (chains). Buried high-angle oblique bedding at windward toes represents evidence of early barchan dune migration. Oblique bedding in upper windward slopes and crests forms through continuous foreset accumulation from superimposed mobile dunes, reflecting frequent aeolian activity in these positions where buried foreset laminae are exposed by wind erosion following dune "fixation and crest reduction." Wedge cross-bedding forms through infilling of wind-eroded pits and troughs on windward slopes or through seasonal wind direction variations at crests.

3) Convex cross-bedding represents upward-curved internal structures of shrub-coppice dunes formed by wind-blown sand accumulation around shrubs. This bedding type is extensively distributed in shallow windward slope layers, with localized occurrences on lower leeward slopes, indicating the important role of superimposed shrub-coppice dunes in modern surface aeolian processes. Deep massive bedding likely results from strong biological activity on early aeolian deposits, causing primary stratification to disappear.

4) The types and assemblage distributions of these internal structures reflect stable or declining barchan dunes undergoing "fixation and crest reduction," characterized by widespread shrub-coppice dunes, common wind erosion troughs on middle-upper windward slopes and crests, gentler leeward slopes with arrested foreset development, and modern aeolian activity concentrated on upper dune portions and crests. These characteristics align with regional environmental changes over the past half-century in northern Xinjiang deserts, including warming and wetting climate trends, decreasing mean wind speeds, and increasing vegetation coverage, though further chronological data are needed for confirmation.

Future work should include cross-profile detection in addition to longitudinal profiles for large-scale barchan dunes (chains) to obtain three-dimensional internal structure images. Additionally, based on characteristics of internal sedimentary structure sequences—such as vertical superposition relationships between shallow high-angle oblique and wedge bedding and deep massive bedding—stratified sampling for optically stimulated luminescence dating to establish a chronological framework for dune depositional sequences would be essential for comprehensively understanding barchan dune evolution processes.

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