Advances and Challenges in Research on Oasis Evolution in the Tarim Basin since the Last Glacial Maximum: Postprint

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Abstract

The oases of the Tarim Basin represent important venues for human production and livelihood throughout historical and modern periods in the arid regions of Central Asia, and constitute crucial nodes along both the ancient Silk Road and the contemporary Silk Road Economic Belt. Investigation of oasis sedimentary records in this region can illuminate oasis evolution processes, thereby facilitating further analysis of the mechanisms governing such evolution. However, intense human activity in the oases surrounding the Tarim Basin has resulted in a scarcity of continuous and complete oasis sedimentary archives; furthermore, the region' s environmental changes are sensitive and complex, with sedimentary records exhibiting characteristics such as "same period, different facies," which constrain explorations of oasis evolution processes and their influencing mechanisms. Consequently, a systematic synthesis of research on Tarim Basin oasis sediments and oasis evolution processes is imperative. Through reviewing current classifications and definitions of oases and oasis sediments, we contend that, beyond geomorphology and sedimentary facies, integration of an indicator system characterizing oasis depositional stages is necessary to better elucidate oasis evolution processes. We selected 24 publications documenting oasis sedimentary sequences in the Tarim Basin since the Last Glacial Maximum and conducted probability density statistical analyses on 232 oasis sediment development ages and 120 fluvial-lacustrine sediment development ages reported therein. Overall, the development ages of oasis sediments and fluvial-lacustrine sediments demonstrate strong consistency, implying that oasis development is intimately linked to intra-basin hydrological processes. Additionally, prior to 6 ka, the probability density of oasis development exhibits concordant variation trends with temperature records from the $\delta^{18}O$ record of the Guliya ice core, suggesting that glacial meltwater from high-altitude regions surrounding the basin may have constituted the primary controlling factor for oasis development; after 6 ka, oasis development aligns more closely with humidity variations recorded in

the loess-paleosol sequence at Lujiaowan in the Tian Shan, indicating that oasis development may have responded principally to changes in orographic precipitation. Further comparative analysis between oasis development probability and paleoenvironmental evolution records across different regions of the Tarim Basin reveals discrepancies between oasis development and paleoenvironmental records among various sub-regions. Future research should pursue integrated investigations of the extensive yet discontinuous oasis sediments across different regions of the Tarim Basin to construct a regional framework for oasis evolution processes and chronology, upon which the factors controlling oasis development in each region can be thoroughly examined.

Full Text

Preamble

Progress and Issues in Research on Oasis Evolution in the Tarim Basin Since the Last Glacial Maximum

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Abstract: Oases in the Tarim Basin represent critical habitats for human production and livelihood in both historical and modern times within the arid regions of Central Asia, serving as vital nodes along the ancient Silk Road and modern Silk Road Economic Belt. Investigating oasis sedimentary records provides essential insights into oasis evolution processes and their underlying mechanisms. However, intense human activity around Tarim Basin oases has resulted in a scarcity of continuous, intact sedimentary sequences. Combined with the region' s sensitive and complex environmental changes and the "same-age heterogeneity" characteristics of depositional records, these factors have limited comprehensive understanding of oasis evolution. Therefore, a systematic synthesis of oasis sediment and evolution research is urgently needed. By review-

ing current classifications and definitions of oases and oasis sediments, we argue that clarifying oasis evolution requires not only consideration of geomorphology and sedimentary facies but also integration of index systems that characterize different oasis developmental stages. We screened 24 publications documenting fluvial-lacustrine deposits since the Last Glacial Maximum in the Tarim Basin, conducting probability density analyses on 232 oasis development ages and 120 fluvial-lacustrine deposit ages. Overall, oasis deposits show good temporal consistency with fluvial-lacustrine deposits, suggesting that oasis development is closely linked to hydrological processes within the basin. Before 6 ka, oasis development probability density correlates with temperature variations recorded in the Guliya ice core, indicating that glacial meltwater from surrounding high mountains may have been the dominant controlling factor. After 6 ka, oasis development shows greater consistency with humidity changes recorded in the Tianshan Luojiawan loess-paleosol sequence, suggesting that mountain precipitation became the primary driver. Further comparison of regional oasis development probability with paleoenvironmental records reveals inconsistencies between oasis development and environmental changes across different Tarim Basin regions. Future research should integrate discontinuous oasis deposits across broader areas, construct regional oasis evolution chronologies, and systematically investigate the factors controlling oasis development in each region.

Keywords: Last Glacial Maximum; oasis evolution; fluvial-lacustrine deposits; Tarim Basin

Oases represent high-productivity, non-zonal geographic and ecological landscapes with stable water supply within arid and semi-arid desert backgrounds. Central Asian arid regions constitute major global oasis distribution areas and the core zone of the Silk Road. The Silk Road traversing the Hexi Corridor and Xinjiang oases served as a critical corridor connecting Eastern and Western civilizations. These oases profoundly influenced the development of Silk Road civilization, with their evolution intimately linked to the rise and fall of civilizations along the route. Simultaneously, oases have served as primary venues for human production and living throughout history, forming green ecological corridors and vital ecological barriers in desert regions, crucial for realizing China' s "Green Silk Road Economic Belt" vision.

Oasis evolution represents a core research question, encompassing oasis expansion/contraction and internal landscape changes. Understanding these processes helps elucidate the mechanisms of oasisification and desertification in arid regions, providing theoretical support for oasis consolidation and ecological optimization. Given the importance of Tarim Basin oases, numerous studies have focused on sedimentary processes and hydrological factors influencing oasis development, identifying pre-oasis and oasis developmental stages. With scarce precipitation, surface runoff hydrology represents the key controlling factor. Researchers have documented widespread fluvial-lacustrine deposits across the basin, interpreted as pre-oasis stage sediments upon which oasis deposits subsequently developed—a conclusion recently confirmed by surface process studies.

Comparative investigations of fluvial-lacustrine and oasis evolution processes enhance understanding of oasis evolution mechanisms.

1 Regional Overview and Research Data

The Tarim Basin (37°–42°N, 75°–95°E) lies in China' s northwest arid region, bounded by the Tianshan Mountains to the north, Pamir Plateau to the west, and Kunlun Mountains to the south. Extending 1,400 km east-west and covering 560,000 km^2, it is China' s largest inland basin. The modern topography slopes from southwest to northeast, with an internal average elevation of 900–1,000 m and surrounding mountains averaging 4,000–5,000 m. The basin exhibits concentric geomorphological zones: mountains, hills, piedmont alluvial fans, alluvial plains, and desert. The basin' s interior is dominated by the Taklamakan Desert (337,000 km^2), with rivers flowing centripetally from surrounding mountains, forming oases along alluvial fan fronts and river courses. The basin experiences a continental climate with annual precipitation of 25–40 mm, potential evaporation of 2,100–3,400 mm, and mean annual temperature of 10–12°C, making it one of China' s driest regions.

To understand oasis evolution, we must first clarify oasis and oasis sediment concepts and classifications. This study reviewed 24 publications on Tarim Basin oasis and fluvial-lacustrine sections since 28 ka, selected based on: (1) coverage of the 28 ka period to identify patterns; (2) long temporal scales with multiple reliable age control points. These include 232 oasis development ages (^{14}C: 98, TL: 14, OSL: 120) and 120 fluvial-lacustrine deposit ages (^{14}C: 14, TL: 14, OSL: 92). For consistency, ^{14}C ages were calibrated to calendar years. While fluvial-lacustrine deposits represent pre-oasis stages, we retain their original classification in cited literature. [Figure 1: see original paper] shows the distribution of these sections.

[Figure 1: see original paper] Locations of the oasis and fluvial-lacustrine deposits profiles in Tarim Basin

2 Research Progress

2.1 Classification of Oases and Oasis Sediments in the Tarim Basin

Previous scholars have defined oases from economic, landscape ecology, and other disciplinary perspectives. Controversies primarily concern oasis distribution boundaries and whether internal human activity is required. Some argue oases are inhabited areas distinct from surroundings, not limited to arid regions; others restrict oases to areas with socioeconomic activity. We propose that: (1) oases are high-productivity landscapes embedded in deserts, potentially containing small desert patches; (2) water is fundamental, requiring stable supply in low-precipitation regions; (3) oases are medium-small scale, non-zonal geographic-ecological landscapes.

Researchers have classified Tarim Basin oases by formation history, geomorphic

position, and human impact degree (Table 2). Oasis sediments are surface/near-surface deposits formed in oasis biological environments. Previous studies distinguished oasis deposits by sedimentary facies, but recent work established an index system using grain size, soil nutrients, and leaching coefficients to differentiate modern oasis, pre-oasis, and desert deposits. Pre-oasis fluvial deposits show finer grain size (70–90 m) but much lower total organic carbon (0.19 $g \cdot kg^{-1}$) and total nitrogen (0.24 $g \cdot kg^{-1}$) than oasis deposits (0.83 $g \cdot kg^{-1}$ and 0.30 $g \cdot kg^{-1}$, respectively). This index system can be applied to sediment profiles to identify oasis developmental stages.

Division and main types of oasis in Tarim Basin

Main types of oasis sediments in Tarim Basin

2.2 Spatiotemporal Evolution Characteristics and Potential Controlling Factors of Oases in the Tarim Basin

We analyzed oasis and fluvial-lacustrine deposit ages using probability density functions (PDF) to express age distributions and identify concentrated geological event intervals. To avoid bias from clustered ages at single archaeological sites, we averaged ages within 0.4 ka bins. This yielded 232 oasis and 120 fluvial-lacustrine deposit ages, processed using Matlab algorithms.

Oasis and fluvial-lacustrine deposits show consistent temporal patterns across the basin, with high development probability density periods coinciding, indicating close linkage between oasis development and internal hydrological processes. Basin precipitation (<50 mm) is insufficient for oasis development, suggesting mountain precipitation or meltwater as primary factors. Comparison with Guliya ice core temperature and Tianshan Luojiawan loess-paleosol humidity records reveals that before 6 ka, oasis development probability correlates with temperature, implying glacier meltwater control. After 6 ka, it aligns with humidity changes, suggesting mountain precipitation dominance.

Regionally, oasis development shows both differences and commonalities. During 28–16 ka, oasis records were sparse except in the Lop Nur area, while fluvial-lacustrine deposits developed mainly in the basin interior. During 16–6 ka, both deposits were widespread. Since 6 ka, oasis deposits have been common across all regions. [Figure 2: see original paper] shows PDF curves for oasis and fluvial-lacustrine deposits with temperature and humidity variations.

[Figure 2: see original paper] Probability density of oasis and fluvial-lacustrine deposits ages and variation characteristics of temperature and humidity around Tarim Basin

Regional analysis reveals complex relationships between oasis development and paleoenvironmental records. During 28–16 ka, peak oasis development occurred in the basin interior and Lop Nur, but not in southern/northern margins. Around 16–13 ka, all regions except the south showed development peaks corresponding to Guliya ice core temperature highs. During 13–7.5

ka, widespread development occurred across all four regions. Northern basin peaks appeared at 8.5–7.5 ka. In the late Holocene (especially after 4.5 ka), development corresponded to humidity increases in Lop Nur and Balikun Lake records, while Guliya temperatures remained high, suggesting combined temperature and humidity controls.

During 2–1 ka, oasis development aligned with humidity increases in Tianshan Luojiawan, basin interior wet phases, and Lop Nur humidity peaks, but with reduced glacier meltwater at Guozha Co, indicating combined mountain and basin humidity influences. Overall, regional oasis development shows both synchronicity and differences, with complex relationships to environmental changes due to varying proxies, carriers, and geographic locations.

2.3 Oasis Evolution and Environmental Change in Different Tarim Basin Regions

Oasis development primarily responded to humidity or temperature changes, but whether controlled by mountain or basin environments remains unclear. Tarim Basin oases served as crucial corridors connecting the Hexi Corridor and Central Asia, linking oasis evolution, human migration, and Silk Road changes. Human activity intensified around 4 ka, corresponding to oasis development peaks, suggesting oases provided foundations for settlement. Studies of Keriya River sites show that settlements migrated with oasis contraction from 2.7–1.6 ka, while Niya and Lop Nur sites demonstrate close human-hydrology-oasis relationships.

3 Main Problems and Prospects

Current research has advanced understanding of Tarim Basin oasis evolution, but several key issues require attention:

First, unified classification of oasis sediments remains unresolved, with unclear correspondence between sedimentary and evolutionary stages. The index system for identifying oasis deposits needs refinement. While modern oasis identification indices exist, their application to sediment profiles requires development.

Second, chronological frameworks remain incomplete, obscuring temporal consistency and spatial patterns. While ^{14}C dating is common, suitable materials are limited to specific stages. OSL dating of quartz and feldspar shows promise for desert and oasis sediments and should be integrated with ^{14}C dating for comprehensive chronological frameworks.

Third, the relative roles of mountain precipitation versus meltwater in controlling basin hydrology remain unresolved. High-resolution mountain records should be compared with basin oasis evolution to identify controlling mechanisms. Before 6 ka, glacier meltwater likely dominated; after 6 ka, mountain precipitation became primary.

Finally, human impacts on oasis evolution require further investigation. Large-scale cultivation and water management historically altered oasis distribution, while hydrological changes and oasis fluctuations affected human activities. Future research should integrate archaeological and historical evidence to clarify human-oasis feedback mechanisms.

4 Conclusions

Based on literature review, Tarim Basin oasis definitions and classifications are well-established, but sediment classification requires clarification. Since the Last Glacial Maximum, oasis evolution shows spatiotemporal heterogeneity. Probability density analyses of oasis and fluvial-lacustrine deposit ages demonstrate close hydrological linkages. Before 6 ka, oasis development correlates with Guliya ice core temperatures, suggesting meltwater control; after 6 ka, it aligns with mountain humidity records, indicating precipitation dominance. Regional oasis development shows both consistency and differences, with complex relationships to environmental changes. Future work should: (1) refine oasis sediment identification indices; (2) conduct extensive dating and integration of discontinuous deposits to build regional chronologies; and (3) investigate mountain environmental records and archaeological data to clarify relationships between oasis evolution, environmental change, human activity, and Silk Road transformations.

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