

# Relationship between the rise and fall of Loulan ancient city and centennial-scale climate events and cycles

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**Abstract** The discovery of Loulan ancient city (LA) in the early 20th century has important significance for understanding the history of Western regions and the Silk Road civilization. The current academic community still has disputes on whether LA was the capital of Loulan Kingdom, the time of its rise, peak and decline, and the process, rate and driving mechanism of human activity change. This study uses the radio carbon dates (<sup>14</sup>C) database of LA to reconstruct the history of the rise and fall of human activity, and finds that LA experienced more than ~500 years from its rise to its peak and then to its decline: 1) the city rose rapidly, and the population increased rapidly from ~A.D. 0 to 230; 2) the city was prosperous and flourishing, and the intensity of human activity reached its peak from ~A.D. 160 to 340, especially in ~A.D. 230, when the population reached its peak; 3) the city accelerated its decline, and the intensity of human activity decreased significantly, and the population shrank rapidly from ~A.D. 230 to 500; 4) LA was completely abandoned after ~A.D. 560. The results of the <sup>14</sup>C dating database do not support that LA was the early capital of the Loulan Kingdom. By comparing the human activity record of LA with the existing high-resolution palaeoclimate records in the surrounding mountainous areas of the Tarim Basin and South Asia, it is found that the superposition of centennial-scale westerly circulation strength events and the ~500-year cycle of the Indian monsoon jointly controlled the precipitation and meltwater (snow) supply of the mountains in the Tarim Basin, affecting the changes of surface runoff and oasis area in

the basin, which is one of the important factors causing the rise and fall of LA.

**Keywords** <sup>14</sup>C probability density, time series analysis, ~500-year cycle, Indian monsoon, westerly circulation

## 1 Introduction

The Loulan ancient city (LA), known as the seat of the Chief Secretary of Western Regions in the Wei and Jin dynasties, was an important city connecting the ancient Silk Road, and was regarded as the political and military center, cultural and commodity exchange hub of Western Regions (Hou, 2001, 2002). Understanding the time, process and mechanism of the rise, prosperity and decline of human activities in the LA is of great significance for a comprehensive understanding of the development history of the Western Regions and the Silk Road civilization (Lü et al., 2010; Zhang et al., 2013; Xu et al., 2017). At the end of the last century, the academic community's understanding of the LA was mainly based on two aspects of evidence: 1) on the one hand, it came from the cultural relics and survey work excavated by archeologists and explorers (Sven, 1898; Giles, 1924; Hou, 1988b; Zuicho, 1994); 2) on the other hand, it came from the direct or indirect records of historical documents, such as: Historical Records, Book of Later Han, Monks' Travel Notes, etc. (Si, 1993; Xuan and Bian, 2006; Fa, 2018; Fan, 2022).

The LA was only the capital of Loulan Kingdom for one historical period, while Loulan Kingdom was a political entity that lasted for several centuries. Loulan

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Kingdom first appeared in the records of the Grand Historian in the Western Han period in B.C. 176, when it was under the rule of the Xiongnu (Si, 1993). In B.C. 77, the Han Dynasty sent someone to assassinate the king of Loulan, and installed Weituqi as the new king, changing the country's name to Shanshan and moving the capital to Yixun city (Shanshan county, Xinjiang) (Ban, 1939). The original Loulan city (Ruoqiang county, Xinjiang) was then occupied by Han troops and a protectorate was established. This period of Loulan city is what we usually call LA (Ban, 1939). However, the Loulan Kingdom did not disappear with the relocation of the capital, but continued to exist in the Western Regions, successively annexing lands such as Ruoqiang, Xiaowan, Jingjue, and Qiemo, and becoming one of the seven powers in the Western Regions. It was only in A.D. 492 that it was destroyed by the Gaoche (Xiao, 2011). And the LA was completely abandoned in A.D. 645 (Fa, 2018).

However, due to the lack of detailed documentary records in key periods and systematic chronological research, there has been a long-standing dispute among scholars about whether the LA was the capital of Loulan Kingdom and the cause of its rise and fall. Whether the Loulan Kingdom moved its capital after being renamed the Shanshan Kingdom has long been debated. The essence of the problem lies in the unification of chronology and geography (Lü et al., 2010). At present, there are four main views. 1) The LA site is the ancient city and capital of Loulan. After renaming, it moved to Tun City (or Qi'erqiduke ancient city), but the LA site did not find any wooden tablets and documents of the two Han dynasties, which raised doubts (Huang, 1996; Hou, 2001, 2002; Xia, 2014). 2) LA site is Tun City, the capital of Loulan and Shanshan kingdoms. It did not move after the renaming (Kazuo, 1992). 3) LA site is the ancient city of Loulan, but not the capital. Tun City (near Ruoqiang County) is the capital of Loulan and Shanshan Kingdoms. There is no problem of moving the capital (Meng, 1990). 4) The capital of Loulan Kingdom is LE (Fangcheng, Square City), not LA site. It moved to Tun City after being renamed (Lin, 1995).

Since the beginning of the 21st century, chronology and environmental archeology have been gradually applied to the archeological research of Loulan, and the following new progress has been made: 1)  $^{14}\text{C}$  chronology evidence determined that the LA was built around B.C. 350 and completely abandoned around A.D. 600. Most of the buildings were concentrated in the ~B.C. 0.25–~A.D. 400 years range, that is, from the end of the Western Han Dynasty to the Eastern Jin Dynasty and the Sixteen Kingdoms period. This evidence also indicated that the LA was most likely the capital of the Loulan Kingdom (Hou, 2002). 2) Environmental archeological evidence shows that from ~B.C. 100 to ~A.D. 500 years period, there were a large number of *Populus euphratica*, reed, Panicoideae, and Eragrostideae herbaceous plants around LA, which was a typical oasis environment. The food

source of the residents was mainly millet, broomcorn millet and barley (Hou, 1985; Zhang et al., 2013; Xu et al., 2017; Li et al., 2019). Around A.D. 600, an important climatic environmental degradation event occurred around the Tarim Basin, mountain glaciers melted, rivers dried up, oasis disappeared, which eventually led to the abandonment of LA (Xu et al., 2017). However, some researchers have put forward different views on the decline of LA, such as overuse of water resources (Mischke et al., 2017); war plague (Yuan and Zhao, 1997) and so on. Due to the limitations of  $^{14}\text{C}$  dating sample quantity, representativeness, quantitative analysis method, and the lack of high-resolution climatic environment records and time series analysis methods, it greatly restricts the comparative study of LA human activity and climatic environment records, historical documents, resulting in the unclear time, process, rate and driving mechanism of human activity change of LA.

In recent years, the  $^{14}\text{C}$  probability density statistical method has been widely used in chronological and environmental archeological research and applied to the study of prehistoric human activities (Wang et al., 2014; Xu et al., 2019; Crema and Bevan, 2021). The basic assumption is that the larger the population, the stronger the intensity of human activity, which can preserve more abundant carbon remains for dating in the site, which is convenient for researchers to obtain (Crema et al., 2016). Therefore, obtaining enough abundant dating data per unit area can greatly improve the accuracy of site dating, which can be used to quantitatively estimate the climax and trough of human activity intensity and semiquantitatively calculate the population change rate (Wang et al., 2014; Xu et al., 2019; Crema and Bevan, 2021). This method has been widely used in Europe (Shennan, 2013), the Americas (Chaput et al., 2015) and Asia (Wang et al., 2014; Crema et al., 2016; Xu et al., 2019) and other regions.

This study uses the  $^{14}\text{C}$  dating database of LA published by previous researchers (Hou, 1985; Lü et al., 2010; Xu et al., 2017; Li et al., 2019) and newly contributed by this study to conduct probability density statistical analysis and compare it with historical documents and existing high-precision dating and high-resolution climatic environment records of time series analysis results in the surrounding areas of Tarim Basin to discuss the process, rate and possible driving mechanism of human activity and population change of LA.

## 2 Materials and methods

### 2.1 The ancient city of Loulan

The Tarim Basin in Xinjiang is located in the heart of the Central Asian arid zone, surrounded by the Tianshan Mountains, the Pamir Plateau, the Western Kunlun Mountains and the Altun Mountains. Glacial (snow)

meltwater from these mountains converges on the Tarim River from different directions and eventually flows through the Tarim River's tributary, the Kongque River, to the lowest point of the basin, Lop Nur (Xia, 2014). At the beginning of the last century, due to climate change and water conservation projects, the upstream supply continued to decrease, and the Lop Nur finally dried up completely in the 1970s (Duan et al., 2013).

The LA (40.516206°N, 89.917769°E) is located on the west bank of Lop Nur in Ruoqiang County, Xinjiang. The city wall is nearly square, with a side length of 327–333 m, and the ancient city covers an area of about 0.108 km<sup>2</sup> (Fig. 1). The main buildings in the city include pagodas, three-room houses and other building groups. At the beginning of the 20th century, Stein numbered each building inside the ancient city (Giles, 1924): the pagoda was LA-X, the platform about 60 m south-east of the pagoda was LA-I, the collapsed house ruins about 80 m south-east of the pagoda were LA-VIII, the three-room house site was LA-II, the large wooden frame west of the three-room house was LA-III, a pile of garbage about 35 m west of the three-room house was LA-VI-ii, a group of large houses west of the garbage pile was LA-IV, a small residence about 10 m west of the three-room house was LA-V, adjacent to The small residence is a slightly more formal residence numbered LA-VI, and a group of small houses about 90 m south of the three-room house is named LA-VII.

## 2.2 Collection of <sup>14</sup>C samples of cereal remains from the ancient city of Loulan and establishment of the <sup>14</sup>C database

During the two scientific expeditions to the LA in 2015

and 2016, we found a large number of cereal remains such as millet, foxtail millet and wheat in the three-room houses LA-II, LA-V, LA-VI, LA-VI-ii, LA-VIII (Fig. 2). In this study, we selected 14 seeds and bran samples from the above five sample points and measured the AMS<sup>14</sup>C age at Beta Laboratory in the United States.

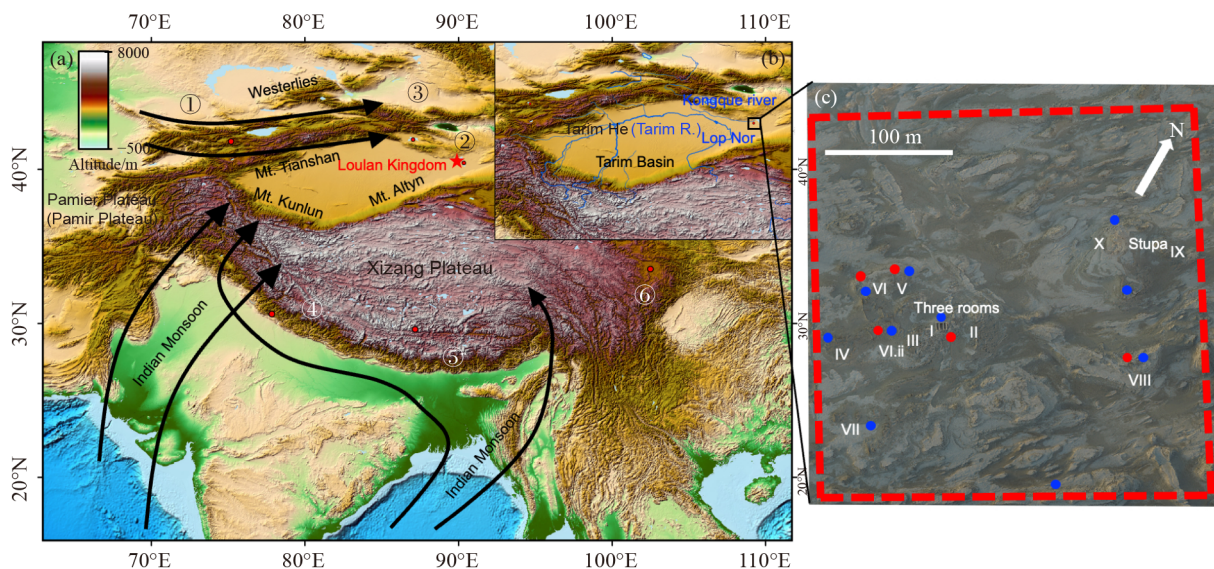
This study also classified the <sup>14</sup>C dating samples accumulated by previous researchers according to the (Stein) site number and material type, and combined with the newly tested seed bran samples, established a <sup>14</sup>C database of the LA (*N* = 49) (Supplementary Material Table S1).

## 2.3 Calculation and verification of <sup>14</sup>C probability density software and methods

### 2.3.1 Calculation and verification of rcarbon software

We used annual seeds and leaves as the most accurate dating materials (Wang et al., 2018), and tested them in the beta laboratory with the intcal20 calibration curve (Reimer et al., 2020), to minimize the dating error. Previous researchers developed the rcarbon tool extension package using the free and open-source R language software, which provides basic functions such as <sup>14</sup>C age correction, merging, visualization, summed probability density (SPD) function statistical analysis and model verification (Crema and Bevan, 2021).

The construction of the probability density function involves two steps: 1) after correcting each <sup>14</sup>C dating result, the probability density distribution curve of each sample is obtained; 2) the probability density of all



**Fig. 1** Location and main buildings of the ancient city of Loulan. (a) The location of the ancient city of Loulan, Son-kol Lake ①, Lop Nur ②, Bosten Lake ③, Sahiya Cave ④, Angrenjin Co ⑤, and Zoige peat ⑥; schematic diagram of the Indian monsoon and westerly circulation (Chen et al., 2019; Zhao et al., 2019). (b) The location of the Tarim Basin, Lop Nur, Tarim River, and Kongque River; (c) The survey map of the main buildings of the ancient city of Loulan (Giles, 1924). Red dashed lines: City walls; Red dots: sampling points of this study; blue dots: sampling points of previous studies.

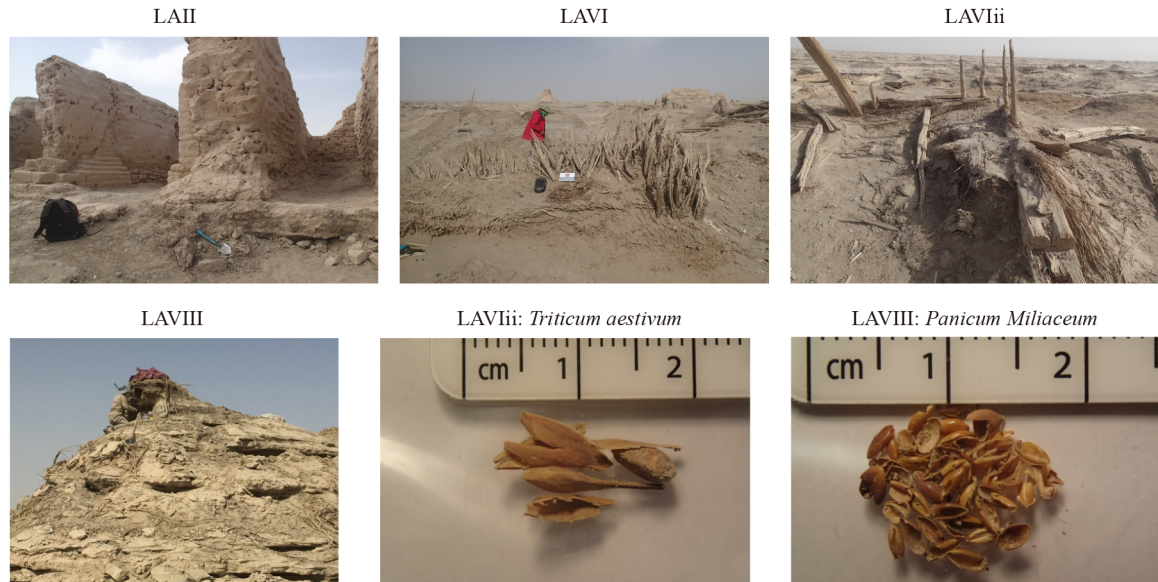


Fig. 2 The sampling points and dating materials of the  $^{14}\text{C}$  samples from the ancient city of Loulan.

samples is added, i.e., the probability density curve of the entire site is obtained. Therefore, the SPD result is closely related to the shape, dating error, and calibration curve of the  $^{14}\text{C}$  probability density curve of each sample (Crema and Bevan, 2021). In this study, the most recent Intcal20 calibration curve was selected for correction (Reimer et al., 2020).

### 2.3.2 Binning and normalization

Differences in the amount of sampling by archeologists at different locations on the site can create artificial signals of oversampling in the SPD results, i.e. “false peaks” or “pseudo valleys” in the SPD (Bevan et al., 2017, 2018; Crema and Bevan, 2021). To reduce this artificial influence, it is necessary to cluster and merge the samples with similar age values at the oversampled locations using a fixed time window (50–200 years range) (Crema and Bevan, 2021). If the clustering and merging results above pass the chi-square test, then this result can be considered as a new age to be included in the overall SPD calculation. If the SPD result does not pass the chi-square test, then these dating results can be treated as independent test ages and included separately in the overall SPD calculation (Wang et al., 2014; Xu et al., 2019).

Since the SPD area after age correction of different samples is different, theoretically each test age must be treated equally, then the SPD area weight of each sample must be normalized and then summed by area superposition (Crema and Bevan, 2021).

### 2.3.3 Statistical model verification

In this study, two models were chosen to test the SPD results.

1) Theoretical growth model verification: previous researchers introduced a series of Monte Carlo simulation testing methods to compare SPD with theoretical models of population change. The confidence level of the SPD curve can be estimated by the Monte Carlo simulation testing method, i.e., the growth, stability and decay curves that are higher/lower than the confidence level (95%) of the theoretical model are considered to be more reliable SPD changes (Shennan, 2013).

2) Testing local growth rates: this method allows the calculated growth rate model to be compared with the expected growth rate model, and only those values that pass the Monte Carlo simulation test (also higher/lower than 95% confidence level) are considered to be highly reliable growth rates/decay rates (Crema and Bevan, 2021). The rate of change (RoC) algorithm is the ratio of the SPD observed in the current year ( $t$ ) to the difference between the SPD in the current year and 50 years ago ( $t-t_{50}$ ):  $\text{RoC} = t/t-t_{50}$ .

## 3 $^{14}\text{C}$ database of the ancient city of Loulan

Table S1 shows the dating results of 49 samples, of which 35 are from previous studies (Hou, 1985; Xu et al., 2017; Li et al., 2019) and another 14 are from new data contributed by this study. The samples from the previous studies are mostly branches of poplar, tamarisk and reed leaves, and only two samples are from camel dung. The samples in this study are all annual crops of millet, foxtail millet seeds and bran. The  $^{14}\text{C}$  dates of previous studies are relatively scattered, ranging from ~B.C. 380–~A.D. 540, with dating errors of  $\pm 25$  to  $\pm 120$  years; the samples in this study are more concentrated, with  $^{14}\text{C}$  dates ranging from ~A.D. 70–270, and the errors are smaller, all  $\pm 30$  years.

Previous studies have suggested that when the number of  $^{14}\text{C}$  samples per million square kilometers is greater than 400, the dating bias caused by insufficient sampling can be effectively avoided (Williams, 2012; Wang et al., 2014; Xu et al., 2019). In addition, our sampling density was converted to  $4.5 \times 10^{14}$  per million square kilometers, which is much higher than the unit space sampling density recommended by previous researchers. In addition, the sampling points basically cover the major site points within the ancient city: including LA-I, LA-II (three-room house), LA-IV, LA-V, LA-VI, LA-VI-ii (garbage pile), LA-VII, LA-VIII, LA-X (pagoda) and south wall samples. Therefore, from the perspective of sampling density and representativeness, it is more reliable to use the  $^{14}\text{C}$  database to reflect the information of human activities in the LA (Williams, 2012; Wang et al., 2014; Xu et al., 2019).

#### 4 Human activity history of the ancient city of Loulan reconstructed by $^{14}\text{C}$ SPD

The SPD result of the LA experienced four main stages (Fig. 3).

1) ~B.C. 500– B.C. 300, the SPD value had a weak increase process (the highest value was ~0.01, confidence level < 95%, did not pass the theoretical growth model test), indicating the sign of human activity, but the population concentration was low, possibly only at the village level scale; ~B.C. 300–B.C. 110, the SPD dropped rapidly to ~0.001, indicating that the intensity of human activity was significantly lower than in the previous period.

2) During ~B.C. 110– A.D. 160, the SPD value increased from ~0.01 to ~0.14, and the RoC growth rate reached up to ~0.025 (confidence level > 95%, passed the local growth rate test), indicating that the population concentration of the LA accelerated and human activity gradually increased; from ~A.D. 0, the SPD slope and RoC growth rate (~0.010–0.025) increased rapidly, reflecting that human activity increased significantly and the population growth rate increased rapidly.

3) During ~A.D. 80– 390, the SPD value was greater than ~0.07 (confidence level > 95%, passed the theoretical growth model test), indicating that both human activity intensity and population size entered a high-level stage; ~A.D. 160– 340, the SPD value was greater than ~0.13, and the RoC growth rate decreased significantly (confidence level < 95%, did not pass the local growth rate test), indicating the peak of human activity; among them, around ~A.D. 230, the SPD reached a maximum value of ~0.17, which was ~17 times higher than that of A.D. 0, indicating that the population size reached the peak of the entire research period, and the city was unprecedentedly prosperous.

4) During ~A.D. 340– 500, the SPD value dropped

significantly from ~0.13 to ~0.01, and the RoC decay rate dropped to ~0.02 (confidence level > 95%, passed the local growth rate test), indicating that the intensity of human activity weakened rapidly and the population shrank rapidly; after ~A.D. 500, the SPD slope and the RoC decay rate began to slow down, approaching zero by ~A.D. 560, indicating that the LA was completely abandoned during this period.

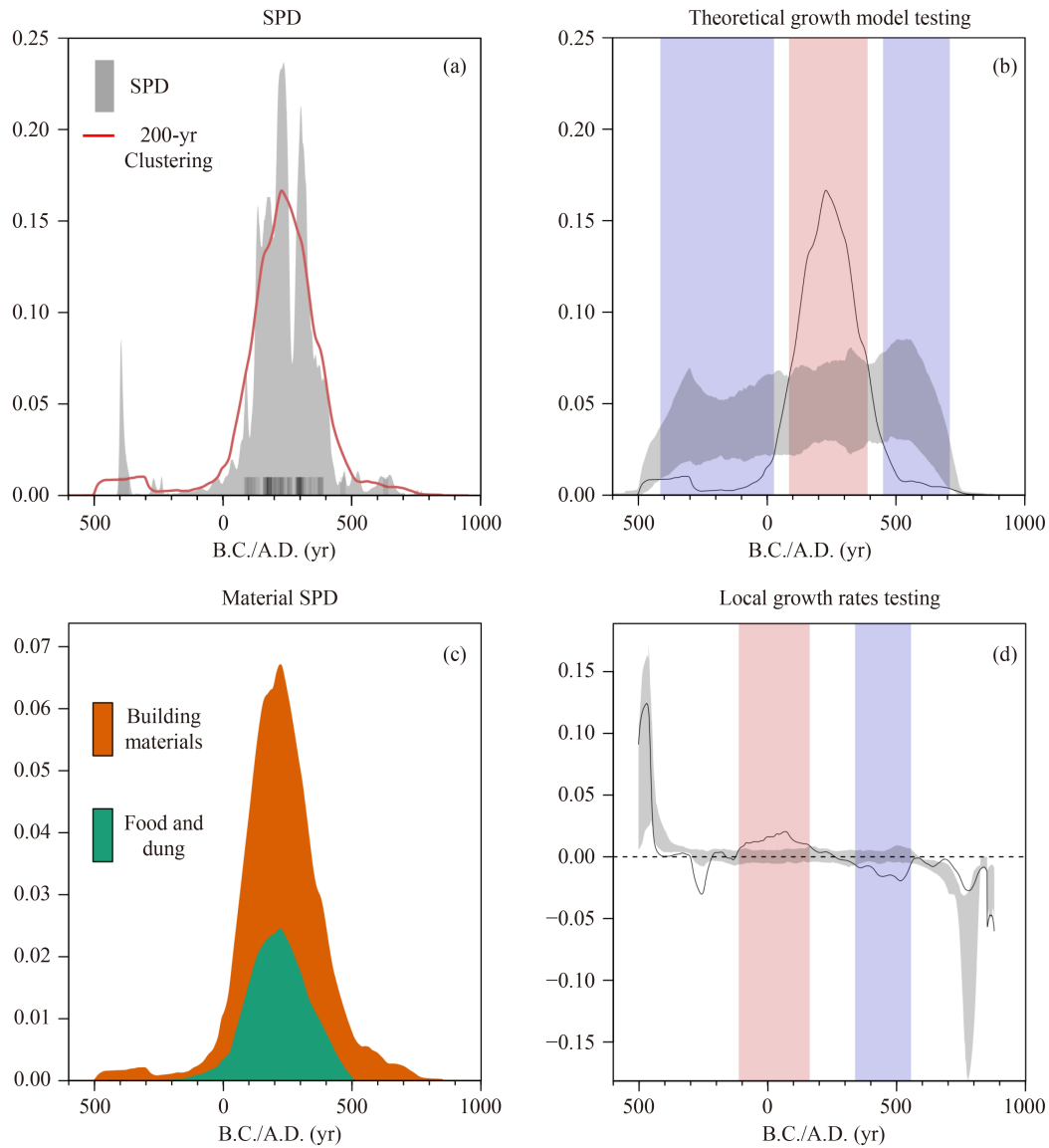
From an overall trend perspective, the population of the LA experienced rapid growth in the early period (~A.D. 0–230), peaked in the middle period (~A.D. 230), and declined rapidly in the late period (~A.D. 230–500), and the prosperity and depression of the city lasted for more than 500 years. It should be noted that the period of high SPD ( $\geq 0.01$ ) of cereal and animal dung remains is relatively more concentrated than that of building material SPD, indicating that agricultural and animal husbandry activities in the ancient city area reached their peak during ~A.D. 50–400 (Fig. 3(c)).

#### 5 Verification of human activity records of the ancient city of Loulan with historical documents and environmental archeological records

The Records of the Grand Historian records that the Kingdom of Loulan existed in B.C. 176 (Si, 1993), but the intensity of human activity in the LA was low during the period of ~B.C. 300– B.C. 110, and the population size was even lower than the village level. Therefore, our evidence is consistent with previous studies (Lü et al., 2010; Xu et al., 2017), and does not support that the LA was the early capital of the Loulan Kingdom.

~A.D. 160–340 was the peak period of human activity, and the documents unearthed from the LA were concentrated in A.D. 263–330 (Hou, 1988a, 1988b), among which the “Li Bai Document” written by the Western Regions Chief Secretary of the Eastern Han Dynasty recorded the year A.D. 328 (Zuicho, 1994), which were all found in the peak period of population concentration in the LA. Therefore, the evidence of human activity and the unearthed documentary materials (Hou, 1988b, 2002) corroborate each other and support the conclusion that the LA was the chief secretariat of the Western Regions in the Eastern Han–Early Liang period.

The camel dung samples collected from the interior of the ancient city, plant macro-remains and phytolith analysis results show that the main crops in the ancient city were millet, foxtail millet and naked barley, and reeds, subfamily Pooideae and shrub plants indicate that this site was a typical oasis landscape during ~A.D. 50–230 (Hou, 1985; Zhang et al., 2013; Li et al., 2019). The wooden tablets excavated from the ancient city contain words such as “sixty-six acres of barley” and “wheat out” (Hou, 1988b). The Book of the Later Han records that



**Fig. 3** Loulan ancient city SPD. (a) Comparison of the original SPD and the cluster merging results of the 200-year time window for LA, the bottom barcode-like stripes indicate the number of cluster merging samples in the 200-year time window (the darker the color, the more clusters); (b) SPD theoretical growth model test results, gray area is 95% confidence line, blue and red stripes are SPD values of growth, stability and decay that exceed 95% confidence line; (c) SPD results of different materials, brown area is SPD results of building materials, green area is SPD results of grain and dung; (d) Local growth rate test results, gray area is 95% confidence line, blue and red stripes are RoC values of growth and decay that exceed 95% confidence line.

Loulan had a history of agriculture (Fan, 2022), and the Commentary on Water Classic records that “a thousand soldiers from Jiuquan and Dunhuang came to Loulan to farm, cutting and irrigating along the Kongque River” (Li, 2020). The wooden slips unearthed at Loulan recorded that “Hu Shi Tian should be ordered to take charge of his field”, suggesting that not only did the garrison troops have fields locally, but that local Hu people could also obtain poorer fields (Hou, 1988b). The historical record of cereal crops and agriculture (Hou, 1988b), the geological record of microorganisms and plant macro remains (Hou, 1985; Zhang et al., 2013; Li et al., 2019), and the cereal remains, and SPD climax period of this study corroborate each other. The oasis

environment provided the necessary conditions for agriculture and reclamation in the ancient city area, and a sufficient grain supply could support the gathering and survival of a large number of people in the ancient city.

During ~A.D. 340–500, the LA showed signs of depression and rapid decay, and the intensity of human activity decreased significantly. The population of ~A.D. 500 shrank to about 1/17 of the ~A.D. 230 period. The wooden tablets excavated from the LA did not record the history after ~A.D. 330, and the excavated cultural relics became scarce after ~A.D. 400 (Hou, 1988a), suggesting that the LA may have lost its status as the chief secretariat of the Western Regions. In addition, Loulan documents show that cultivation and irrigation continued until ~A.D.

330 (Xia, 2014). The last time Loulan appeared in historical records was when Faxian went west in search of sutras in ~A.D. 399, passing through Shanshan (Loulan) and staying there for a month (Fa, 2018). He wrote in *A Record of Buddhist Kingdoms* that although there were many monks in the city of Loulan, the land was very barren and no longer suitable for living (Fa, 2018). After seeking the Dharma in India, Xuanzang returned to China via the LA in A.D. 645 and found that the city had been abandoned long ago (Xuan and Bian, 2006). This study shows that the abandonment time of the LA ~A.D. 560 is consistent with historical data, later than A.D. 399 but earlier than A.D. 645, slightly earlier than the abandonment time ~A.D. 600 proposed by previous studies (Xu et al., 2017).

Based on historical documents and our dating evidence, we believe that ancient Loulan kingdom had carried out capital relocation activities, and LA was the capital of Loulan kingdom in the middle and late periods.

## 6 The influence of centennial-scale climate events and cycles on the rise and fall of the ancient city of Loulan

For a long time, scholars have had different opinions on the causes of the decline of the LA, such as climate degradation events, wars, plagues, etc. (Xu et al., 2017). In recent years, new geological records seem to support that the decline of the LA was caused by centennial-scale climate events (Zhang et al., 2013; Xu et al., 2017; Li et al., 2019). Recently, some high-precision dated climate records from the Tibetan Plateau region have documented centennial-scale climate events or cycles, which had important impacts on the adjacent regional cultures and civilizations (Kathayat et al., 2017; Li et al., 2021). We selected high-resolution climate records from the Tianshan Mountains and the Tarim Basin, which are influenced by the westerly circulation (Wünnemann et al., 2006; Ma et al., 2008; Lauterbach et al., 2014), and the peripheral areas of the Tibetan Plateau, which are influenced by the Indian monsoon (Kathayat et al., 2017; Liang et al., 2020; Li et al., 2021), for time series analysis, and found that the Indian monsoon has a significant ~500-year cycle variability (Fig. 3) (Liang et al., 2020; Li et al., 2021).

The time series analysis results show that during ~B.C. 100–A.D. 500, the strengthening and weakening events of the westerly circulation were almost in phase with and superimposed on the strengthening and weakening of the ~500-year cycle of the Indian monsoon (Fig. 4).

1) The Son-kol Lake, Bosten Lake and Lop Nur records show that the Tianshan glacial meltwater (snow) experienced an increase (~B.C. 100– ~A.D. 200) and a decrease (~A.D. 200– 500) during ~B.C. 100– A.D. 500, and the meltwater (snow) amount peaked at ~A.D. 200, indicating that the westerly circulation supplied water

vapor to the Tianshan Mountains at its strongest stage; during ~A.D. 700– 900 and ~A.D. 1400– 1700, the Tianshan meltwater (snow) amount increased slightly, indicating that the westerly intensity increased to some extent, but never reached the level of ~A.D. 200 (Wünnemann et al., 2006; Ma et al., 2008; Lauterbach et al., 2014).

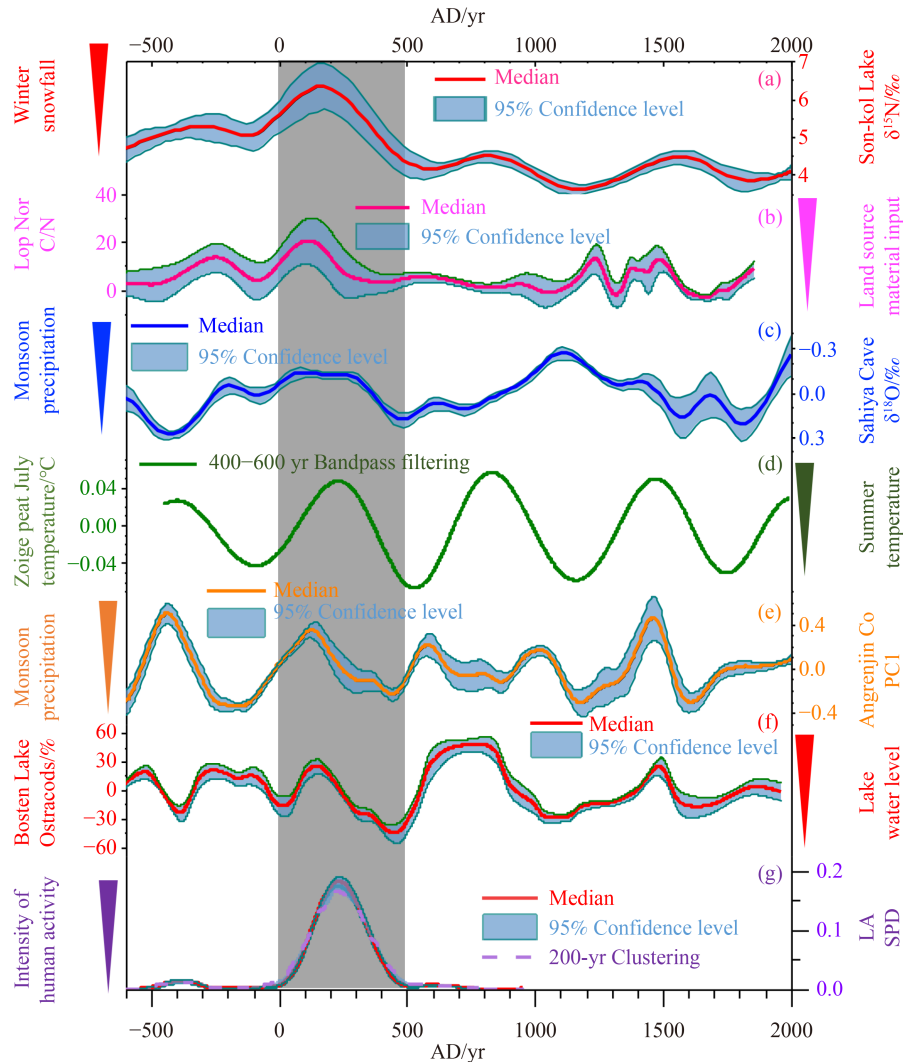
2) Oxygen isotope records from the Sahiya Cave stalagmite in south-western Tibet (Kathayat et al., 2017), Angrenjin Co in southern Tibet (Li et al., 2021), and Zoige peat pollen in eastern Tibet (Liang et al., 2020) indicate that the Indian monsoon has a stable and significant ~500-year cycle (Fig. 4). The three records all show that the Indian monsoon began to intensify around ~B.C. 100– A.D. 0, reached its peak around ~A.D. 200– 300, and then declined to its lowest point around ~A.D. 500. The changes in the intensity of human activity and the size of the population of the LA were almost synchronous with, or slightly lagged behind, the changes in the westerly circulation and the intensity of the Indian monsoon (Fig. 4). How did the Indian monsoon superimpose on the westerly circulation to influence environmental changes in the Tarim Basin?

The Central Asian pollen record shows that during ~B.C. 100– ~A.D. 200, Indian monsoon water vapor could reach the Pamir Plateau through the southern and western channels of the Tibetan Plateau and influence the environmental changes in the Tarim Basin through glacial meltwater (snow) (Zhao et al., 2019). Moreover, modern (Huang et al., 2015) and Holocene (Zhang and Jin, 2016) simulation results show that the Indian monsoon is an important contributor to summer precipitation in the mountainous areas surrounding the Tarim Basin (such as Tianshan, Western Kunlun Mountains, Pamir Plateau).

Combining geological records and simulation results, we believe that the Indian monsoon and the westerly circulation jointly regulate the amount of glacial meltwater (snow) in the mountainous areas around the basin and drive the changes in river discharge and Lop Nur oasis area in the Tarim Basin. Therefore, it is likely that the superposition of the centennial-scale westerly circulation climate events and the ~500-cycle Indian monsoon led to the rise and fall process of the LA for more than 500 years.

During ~A.D. 500– 800, there was still evidence of human activity in the area of the LA, but the SPD intensity of human activity indicated that the scale was only equivalent to the early village level.

It should be noted that the ~500-year cycle is superimposed on the overall weakening trend of the Holocene Indian monsoon (Zhang and Jin, 2016; Kathayat et al., 2017; Zhao et al., 2019; Li et al., 2021); the water vapor transport of the Indian monsoon to the Pamir Plateau and Tarim Basin showed a significant weakening after ~A.D. 200 (Zhao et al., 2019), and at the same time there was a major climate event of weakening of the westerly circulation and significant reduction of



**Fig. 4** Comparison of the SPD of the ancient city of Loulan and the palaeoclimate records. (a) Nitrogen isotope self-sampling sliding average results from Son-kol Lake in the Tianshan Mountains, red line median, blue strip 95% confidence interval. (b) Carbon to nitrogen ratio self-sampling sliding average results from Lop Nur in the east Tarim Basin, pink line median, blue strip 95% confidence interval. (c) Oxygen isotope self-sampling sliding average results of Sahiya Cave in India, blue line median, blue strip 95% confidence interval. (d) July average temperature 400–600 year band-pass filtering results of Zoige peat in eastern Tibet. (e) Pollen first principal component self-sampling sliding average results of Angrenjin Co, yellow line median, blue strip 95% confidence interval. (f) Moisture proxy self-sampling sliding average results from Bosten Lake in the east Tarim Basin, red line median, blue strip 95% confidence interval. (g) LA SPD self-sampling sliding average results, purple line 200-year time window cluster merging results, red line median, blue strip 95% confidence interval. The gray strip indicates the rise and fall period of the LA.

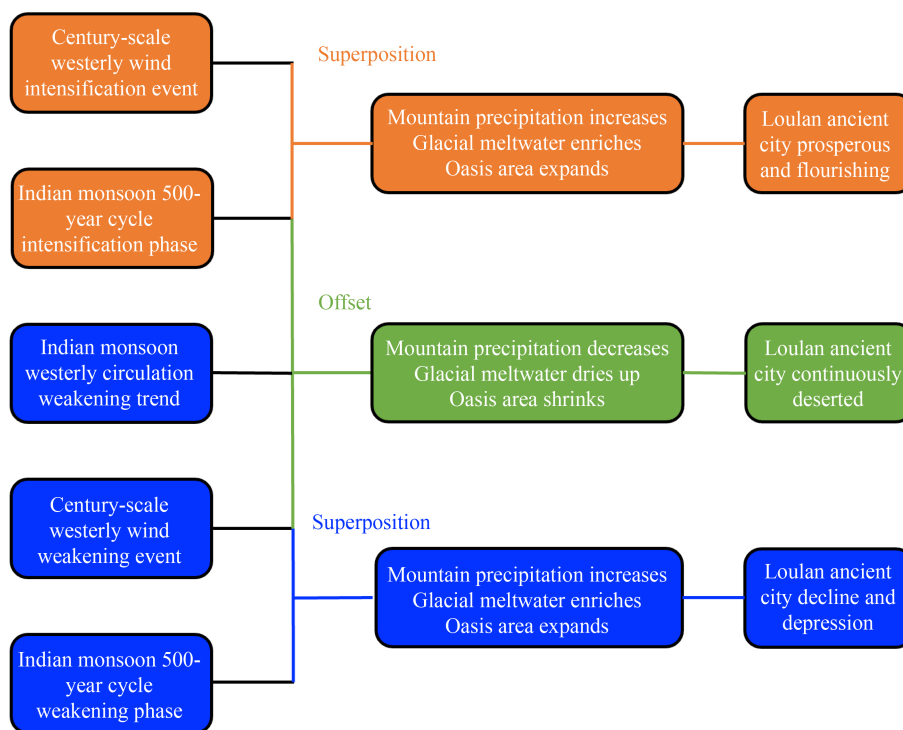
Tianshan glacial meltwater (snow) (Lauterbach et al., 2014). After the superposition of these two factors, even when the Indian monsoon reappeared in the ~500-year cycle of prosperity (Fig. 5), the weak water vapor supply from the surrounding mountains could not produce enough glacial meltwater (snow) to support the large-scale recovery of the Lop Nur oasis downstream. These factors are likely to be one of the main reasons why the LA was unable to regain its former prosperity after its decline in the A.D. 6th century.

Although this study supports that climate change is one of the reasons for the final abandonment of the LA, there are often multiple aspects to the abandonment of ancient

cities. Human overexploitation of water resources (Mischke et al., 2017) and the effects of war and plague (Yuan and Zhao, 1997; Xu et al., 2017) may also play an important role. Therefore, future research should combine multiple disciplines and indicators to understand the detailed processes and causes of the rise and fall of the LA.

## 7 Conclusions

Human activity in the LA went through three stages: in the early stage, ~A.D. 0–230, the population gathered



**Fig. 5** Possible driving mechanism for the rise and fall of the ancient city of Loulan.

rapidly and human activity increased significantly, and the city continued to prosper and develop; in the middle stage, ~A.D. 160–340, the degree of population gathering reached its peak, and the intensity of human activity peaked at ~A.D. 230, and the city was unprecedentedly prosperous; in the late stage, ~A.D. 230–500, the city showed a declining trend, the population decreased rapidly, and the intensity of human activity weakened rapidly; in ~A.D. 560, the ancient city was finally abandoned.

The ~500-year Indian monsoon cycle had a profound impact on the development of civilization in the Lop Nur region. It was superimposed on the intensity events of the westerly circulation and together led to the rise and fall of the LA: the strengthening of the westerly circulation and the positive phase superposition of the ~500-year Indian monsoon cycle promoted abundant precipitation and an increase in glacial meltwater (snow) in the mountainous areas around the Tarim Basin, increased river runoff, expanded the Lop Nur oasis area, and made the LA prosperous; the weakening of the westerly circulation and the superposition of the negative phase of the 500-year Indian monsoon cycle led to a significant decrease in precipitation and glacial meltwater (snow) in the mountainous areas around the Tarim Basin, decreased river runoff, shrank the Lop Nur oasis, and caused the LA to decline.

The ~500-year cycle is superimposed on the general weakening trend of the westerly circulation and the Indian monsoon. After the decline of the LA, the overall weakening trend of the westerly circulation and the

Indian monsoon offset the reappearance of the strong period of the ~500-year Indian monsoon cycle. Therefore, it seems that no single factor alone can drive the revival of the LA.

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