




# New evidence of agricultural activity and environmental change associated with the ancient Loulan kingdom, China, around 1500 years ago

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## Abstract

The ancient kingdom of Loulan on China's Silk Road has disappeared for about 1500 years. Historical records have documented widespread cultivation in Loulan which supported the kingdom's prosperity for hundreds of years. However, no farmland ruins have been found although the ancient Loulan city was discovered more than 100 years ago. In this study, remotely sensed, geomorphic and geological observations of possible farmlands in Loulan were analyzed. A wide distribution of partly preserved plots with recognizable regular and straight boundaries, the existence of crossed canals, the occurrence of a gypseous incrustation layer (GIL) overlying on the surface of farmland-like blocks, and extracted large-sized pollen grains of cultivated grass from GIL samples provide new evidence for the ancient farmlands. Field observations revealed that the upper cultivated soil layer overlaid on GIL, i.e. soil horizon A, had been wind-eroded and GIL is the ruined soil horizon B. These new findings point to a well-developed agriculture of the ancient Loulan kingdom. The size and distribution of the farmlands and the thickness of the GIL suggests that irrigation for cultivation in this currently exceedingly arid area had lasted for a long time. Fluvial and lacustrine sediments in Loulan area deposited during the about 4 to ~8 ka BP period, revealing that the wet Holocene optimum and two arid events of about 4 and 8 ka BP occurred in the westerlies-dominated northwest China. The Loulan kingdom period was another wet stage when the ecological environment was the typical cultivated grass of oasis near wetland. The insufficiency of water during the late period of the Loulan kingdom led the decline of irrigation agriculture and finally the renunciation of the kingdom.

## Keywords

ancient Loulan, cultivation, large sized pollen, Lop Nur of Xinjiang, paleoclimate, ruined farmland

## Introduction

Ancient Loulan city (N40°30'58.73", E89°54'51.73") is located on the western bank of lake Lop Nur in Ruoqiang county of Xinjiang, China. It is situated around the eastern corner of Tarim basin (Figure 1) which is the largest sedimentary basin to the north of the Tibetan Plateau. Although Lop Nur is known to be the depositional centre of the Tarim basin and was the largest lake in western China, the formation and evolution of the lake and the environmental change around the lake during the geological time remain a topic of hot debate (Cheng, 1936; Hedin, 1926; Huntington, 1907; Village Sydney, 1955; Xia et al., 2007). The region is now predominately under the influence of the westerlies, with climate conditions in marked contrast to the region affected by the East Asian monsoon. It developed into the core arid area of Eurasia from at least the beginning of the Quaternary period (Zhu et al., 1981). However, there were numerous oases in the basin which had supported many ancient kingdoms along the ancient Silk Road. Loulan was one of 36 ancient kingdoms of western regions during the Former Han Dynasty of China described in the historical literature *Hanshu* written by Ban Gu (i.e. Pan Ku) (92).

Loulan was a prosperous and strong kingdom from 77 BC (Ban, 92; Faxian, 416; Li, 466–527; Xia et al., 2007). However, the kingdom completely disappeared and the region with an area of tens of thousands of square kilometers was strongly

wind-eroded and became an uninhabitable Yardang area after Monk Xuanzang of the Chinese Tang Dynasty passed through the ancient kingdom in about AD 645 (Xuanzang, 645). Investigation into the area has been very difficult because of the lack of roads and fresh water. In 1899, ancient Loulan city was rediscovered by S. Hedin (Hedin, 1926). He excavated ruined houses and found wooden tablets and many Chinese manuscripts from the later Han Dynasty to Former Liang Dynasty of China (the third century AD). M.A. Stein made further excavations in 1906 and 1914 (Stein, 1912, 1921). Since then, many explorers from different countries

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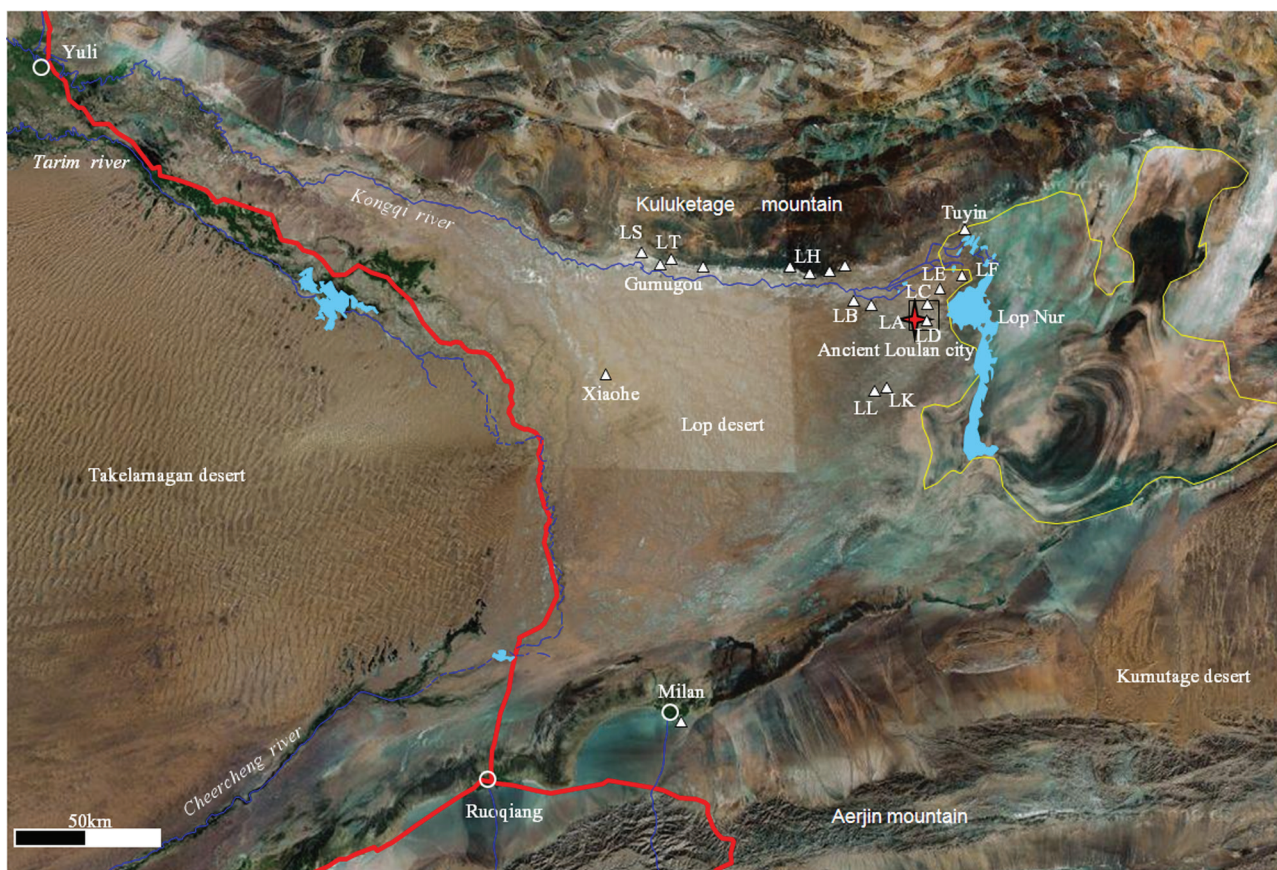
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**Figure 1.** Location of the ancient Loulan city (red star) and Lop Nur (black box is the range of Figure 3). White triangles are ruined sites and letters are their names. Red lines are highway, the blue line is the river. White circles are cities or towns. The cyan area is lake. Cyan Lop Nur lake dried in 1973 (Xia et al., 2007). The yellow line is ancient Lop Nur existing before cyan lake. Image is from map.google.com

have investigated Loulan (cf. Xia et al., 2007). Bergman (1935) discovered the Xiaohe Tomb complex, a Bronze Age burial site, to the west of the Loulan city in 1934. These early findings made Loulan famous and important for studying cultural exchange between the West and the Orient. The most recent finding was an ancient city of the Northern Wei Dynasty near Xiaohe tumulus (Lu et al., 2010).

Historical literature showed that agriculture was once flourishing in the Loulan kingdom (Ban, 92; Faxian, 416; Li, 466–527). The earliest literal record of cultivation in Loulan was in Li Daoyuan's book *Shuijingzhu* of the Northern Wei Dynasty of China (Ban, 92; Li, 466–527). Formerly, the ancient Loulan indigenes employed grazing. In about 70 BC, Chinese General Suo Mai (i.e. So Man) led 4000 soldiers for a three-day campaign to block out Zhubin river (i.e. the ancient Tarim river) in order to create an irrigation system for the farmlands. The indigenes were shocked and surprised by the bumper crop harvest in the sequential three years. The records clearly indicate that the cultivation and irrigation technique of the ancient Loulan kingdom can be traced back to Chinese Han Dynasty. The most detailed records of cultivation in Loulan came from wooden tablets and papery manuscripts found in the ruined sites of Loulan (Xia et al., 2007; Zhang, 2001). The tablets and manuscripts were written about AD 270–330. For example, a tablet (753, LA, VI, ii) carries a description that 29 mu of 37 mu wheat farmland had been planted and 20 mu of 1 qing 85 mu millet farmland (mu and qing are units of area, 1 qing = 100 mu = 6.6667 ha) had been irrigated by Zhang Lian's troops with 21 soldiers (Zhang, 2001). From the well

documented number of soldiers involved, the area of farmland and the type of crops, it is clear that farmlands were irrigated even though water was in short supply. However, there has been a lack of direct physical evidence for the ancient farmlands and canals at Loulan, despite all the historical records on farmland in the area. The only known physical evidence of Loulan farmland was a farmhouse ruin found by Stein in 1914 (Stein, 1921; Xia et al., 2007) at about 4 km east of the ancient Loulan city and a man-made canal reported by a Chinese archaeological team in 1979–1980 (Hoh, 2005; Integrated Survey Team for Lop Nur Lake, 1987). Over nearly a century the search for more direct evidence of farmland in the ancient Loulan kingdom has never stopped and the history of agriculture in this extremely arid area and the causes for its sudden demise remain a mystery of world attention.

The environment of the ancient Loulan indigenes was another issue for attention. However, most discussion was focused on the evolution, location and distribution of lake Lop Nur in nearly a hundred years. For example, the Russia officer Nikolai Przhevalsky proposed the Kara Heshun Lake to be the ancient Lop Nur but German geographer Ferdinand von Richthofen believed them to be two different lakes (cf. Xia et al., 2007). Huntington (1907) put forward the 'Lake of profit and loss' and the rationale for it, but Hedin (1926) believed Lop Nur to be the 'wandering lake' with a north–south wavering cycle of 1500 years; and the Chinese scholar Cheng (1936) developed it as an erosion and deposition-driven 'turn of Lake' viewpoint of Lop Nur. The Soviet Union geologist Village Sydney (1955) suggested that tectonic movement led to the Lop Nur wavering. Although arguments lasted a

**Table 1.** OSL dating samples from the Pagoda section in Loulan city

Sample number	TDP3-1	TDP3-3	TDP3-3	TDP3-4
Depth (cm)	30	220	390	540
De (Gy)	16.05±1.22	19.18±3.13	21.36±1.09	39.57±1.60
K (%)	1.81±0.043	1.64±0.041	1.88±0.045	2.02±0.042
U (ppm)	2.52±0.051	2.57±0.098	2.12±0.091	3.67±0.121
Th (ppm)	9.84±0.295	9.84±0.295	8.30±0.266	10.8±0.313
Moisture (%)	15±5	15±5	15±5	15±5
u (Gy/yr)	3281±178	3096±173	3016±166	3760±213
Age (yr)	4900±450	6200±1100	7100±500	10500±700

century, the environment of the region that supported the flourishing ancient Loulan was unclear for a long time.

In this study, we report new evidence for farmlands in the surroundings of the ancient Loulan kingdom. We also present preliminary results of a study on the Holocene environment of the Loulan region according to a sedimentary sequence and irrigation ruins.

## Materials and methods

Field investigations were carried out in June and December of 2008 and October of 2010, respectively. High spatial resolution satellite images of Google Earth were carefully analyzed prior to the fieldwork and several farmland-like and canal-like features were identified. These sites were surveyed during the fieldwork and their geometry was measured and recorded. Surface soils were sampled from farmland-like sites and from other areas for pollen analysis. A 6 m sediment section under a Pagoda in the ancient Loulan city was sampled at 5 cm intervals. Four samples from the section at 0.3 m, 2.2 m, 3.9 m and 5.4 m, respectively, were dated by the optically stimulated luminescence (OSL) method.

Magnetic susceptibility (MS) and grain size of sediment samples from the Pagoda section were measured using a Bartington MS2 susceptibility meter and a Malvern Mastersizer 2000 particle analyzer, respectively, based on the same protocols used by Qin et al. (2005). Samples for OSL dating were prepared under subdued red light at the Luminescence Dating Laboratory of Peking University. Hydrochloric acid (10%) and hydrogen peroxide (30%) were used to remove carbonate and organic matter. Several fractions of varying sizes were obtained by sieving and setting. As it was unsuccessful in extracting quartz grains with the 45–63  $\mu\text{m}$  fraction using  $\text{H}_2\text{SiF}_6$ , polymineral 63–90  $\mu\text{m}$  fraction was used for luminescence measurements. Equivalent dose (De) determination was done using the procedure of Buylaert et al. (2009). Dose rates were calculated from the measured Y, Th and K content (Table 1).

Several soil samples were analysed on a D/max 2400 x-ray diffractometer to determine their mineral compositions. Soil samples for pollen analysis were treated with HCl–NaOH–HF method described by Faegri et al. (1989) and Moore et al. (1991). About 30–100 g soil sample was mixed with a Lycopodium spore tablet (27 637 grains) as a tracer. The HCl (36%) treatment was used to remove carbonate, the NaOH (5%) treatment was to remove organic matter and the HF (40%) treatment was to remove siliceous materials. Wet sieve (sieve diameter is 10  $\mu\text{m}$ ) treatment with an ultrasonic cleaner was used to remove fine material. Collected residue was again separated from undigested mineral detritus by using heavy liquid (specific gravity 1.9), and followed by acetolysis to remove unwanted matter such as cellulose and

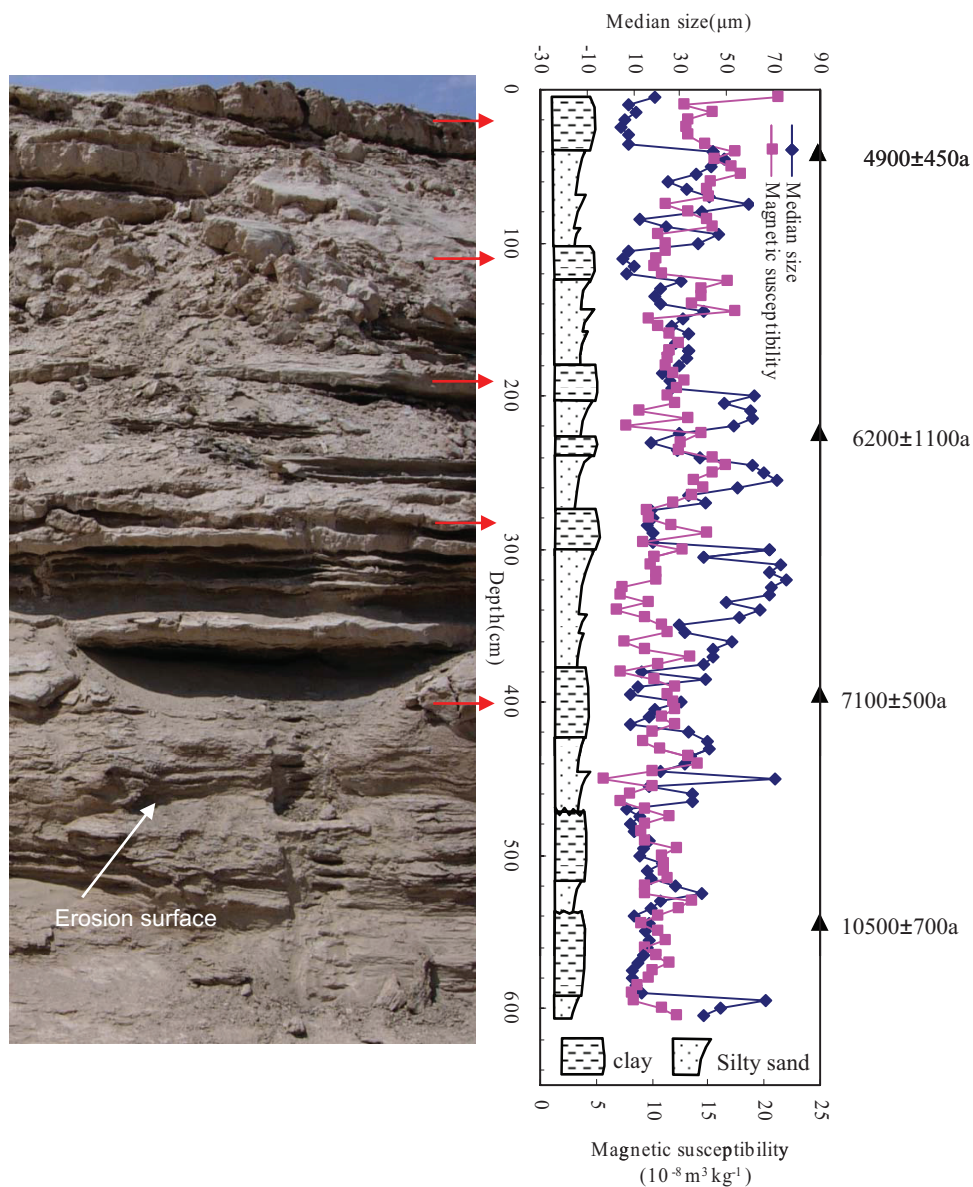
humic debris. Fossil pollen were identified and counted with an Olympus microscope at 400  $\times$  magnification.

## Results

### Sediment of Loulan area

The ancient city of Loulan was located at the western bank of Lop Nur Lake that had been completely dried out in 1973 (Xia et al., 2007). The region is now covered by Quaternary fluvial and lacustrine sediments that consist of clay and silty sand alternations (Figure 2). The finer, compact and hard clay layers are considered to indicate the relatively greater depth of lake water while the coarser, loose silty sand layers may represent the environment of the lake offshore or fluviation. In the Loulan Pagoda sediment section, there was no sulphate mineral (gypsum) deposition. There is an erosion surface at about 4.65 m depth, implying that the area had been exposed and eroded. Based on the preliminary OSL dates in Figure 2, the erosion took place around 8 ka and was a several hundred year arid event. Buildings in ancient Loulan city, such as the pagoda and the three-rooms, were constructed on a hard clay layer at the sediment's top. The sand formation under the top compact clay layer is dated to about 4.9 ka, suggesting that about 4 ka BP was the start of a lasting arid period. This has gradually led to the shrinkage of the ancient lake and retreat of the lake coast. As a result, the western coastal area of the Lop Nur was exposed, providing vast land for the ancient Loulan people. Both the arid events of about 4 ka BP and about 8 ka BP were also widely found in the Eastern Asian monsoon region (Shi and Kong, 1992). Repeated occurrence of the clay layers indicates that the ancient Lop Nur Lake flooded the whole Loulan region several times during Holocene Optimum (from ~4 to ~8 ka BP). It suggested that the lake area was larger than the ancient lake shown by a yellow line in Figure 1.

As the rainfall in Tarim basin was extremely low, lake water mainly came from surrounding mountains. Thus, the rainfall in the mountains was abundant because of high global air temperatures during the Holocene optimum period. It means that the paleoclimate in the westerlies-dominated core arid area of Eurasia was similar to that in the Eastern Asian monsoon region during the Holocene optimum. It was noticed that the MS of the samples under the eroded surface at 4.65 m was markedly lower than that above the eroded surface. It implies that the material source before 8 ka BP may be different from that during Holocene optimal period because the MS of lake sediments was usually positively correlated with the amount of inorganic allochthonous material (Thompson et al., 1975). It can be concluded that global climate events, including the wet Holocene Optimum and two arid events of ~4 ka BP and ~8 ka BP, took place in the westerlies-dominated west of China.



**Figure 2.** Quaternary sediments (Loulan Pagoda Section) of fluvial and lacustrine facies that consisted of clay and silty sand alternations in the ancient Loulan city (arrows indicate clay layers. Black triangles are locations of OSL-age samples and values on right are measured OSL-ages)

### Landforms of the Loulan area

Wind-eroded Yardang dominates the landforms of the Loulan area because precipitation in Lop Nur area is extremely low (<20 mm/yr) and there is a prevailing northeasterly wind. Yardang consists of NE-extended hillocks and grooves. Particulate materials were blown by wind to form the Lop desert. The tops of ruined hillocks indicate the ancient ground surface. Most of the hillocks in Loulan are about 0.5–2 m high and represent the height of the latest Yardang that developed after Loulan was abandoned. A few of the Yardang hillocks, such as the LC Han-Wei Dynastic tumulus-built high hillock (Xia et al., 2007), are about 8–9 m high. They represent residual hills formed in an earlier wind-eroded Yardang period.

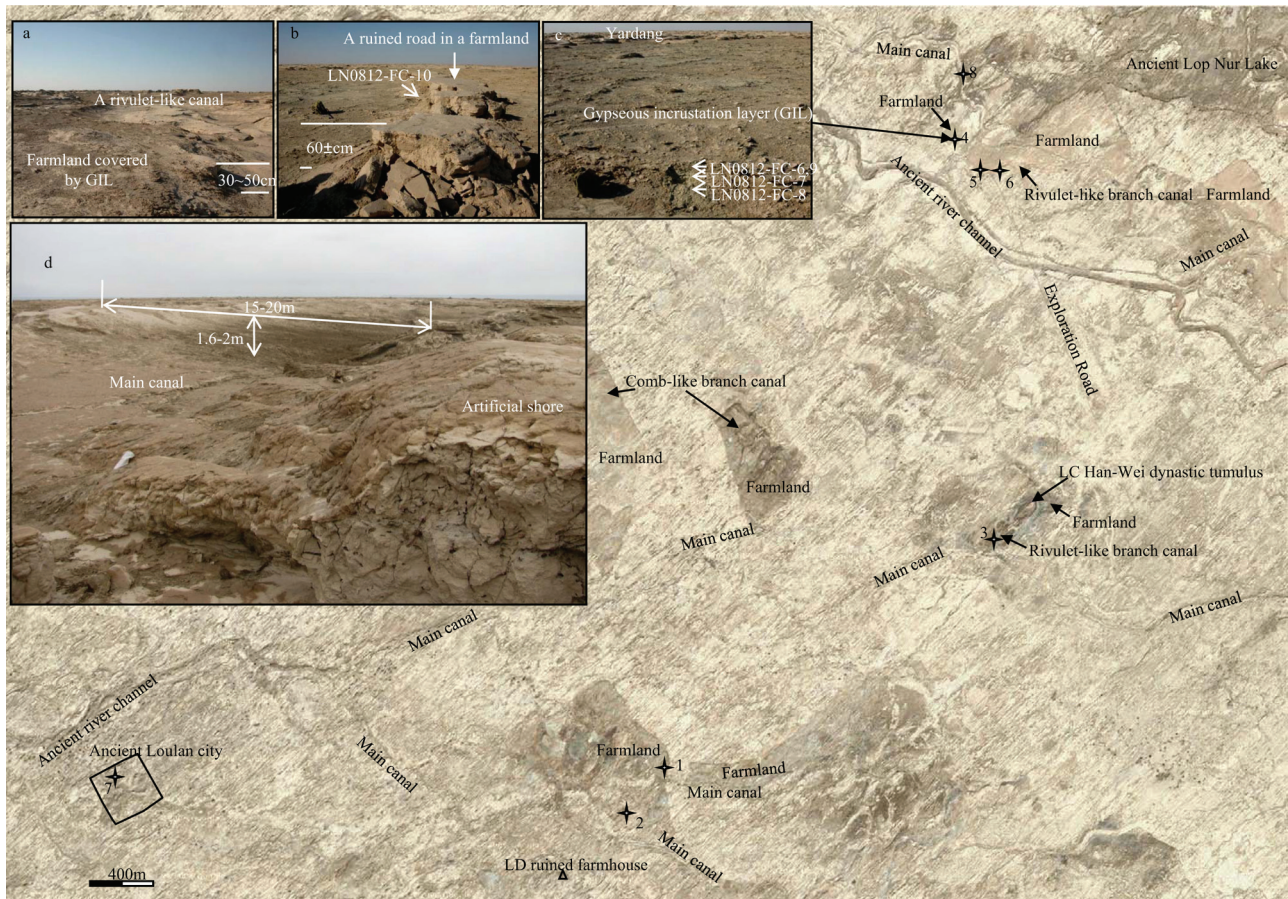
### Morphological features of ancient farmlands and canals

On remotely sensed images, the most obvious objects in the Loulan area are regular blocks with straight boundaries (Figure 3). The colour of these blocks is darker and can be divided into two tones: grey black and dark red. NW-extended boundaries of these

blocks crossed NE-extended Yardang hillocks, implying that these features are non-natural and artificial objects. The length of the block boundaries is from 200 m to 1000 m. There are always canals passing nearby or crossing through these blocks, suggesting that the blocks were related to water utilization.

There are two distribution patterns of branch canal in the blocks. One is that canals crossed transversely through a block, known as comb-like canal. Another pattern is that a canal crossed through blocks along a natural squiggly rivulet on which there were a few manmade construction ruins, known as rivulet-like canal. In most farmland-like blocks, Yardang is poorly developed and the ground surface is flat and about 0.3–1 m higher than the beds of adjacent branch canals. We speculate that these farmland-like blocks were purpose-designed to facilitate irrigation.

Main canals, like the upstream of branch canals, are always linked with a natural river channel. Usually, most main canals are relatively smooth and straight, their bed consists of a clay layer and their manmade banks look different from the water-eroded levee banks in natural rivers. The field observation at site No. 8 revealed that the main canal has a channel bed with an arc-shaped



**Figure 3.** Farmlands and canals in northeast of ancient Loulan city. (a) A rivulet-like canal. (b) The position of LN0812-FC-10 from the foot of a ruined road within farmland. (c) Sampled depths of LN0812-FC-6~9 in GIL. (d) Photo of a major canal. numbers are sampled site: 1, LN0812-3; 2, LN0812-142-1,2,3 sampled from the top green GIL, the middle red GIL and the bottom silty sand sediment, respectively; 3, LN0812-FC-13; 4, LN0812-6~10 and site of photo (b,c); 5, LN0812-FC-11 and the site where stoneware found; 6, site of photo (a); 7, location of Loulan Pagoda section; 8, site of photo (d) Background image from map.Google.com

cross-section. The artificial bank, 15~20 m wide and 1.6~2 m deep (Figure 3d), is completely different from a nearby natural river which is 8~9 m deep, 40~60 m wide with typical water-eroded levee banks. There were some fossils of aquatic snail on the canal bed surface, indicating that water flowed through the canal in the past, although now the canal bed is higher than the surrounding ground. Both ends of the canal were connected to a natural river, implying that the function of the canal may have been for inter-river water transfer and/or for shipping.

#### Field evidence of farmlands

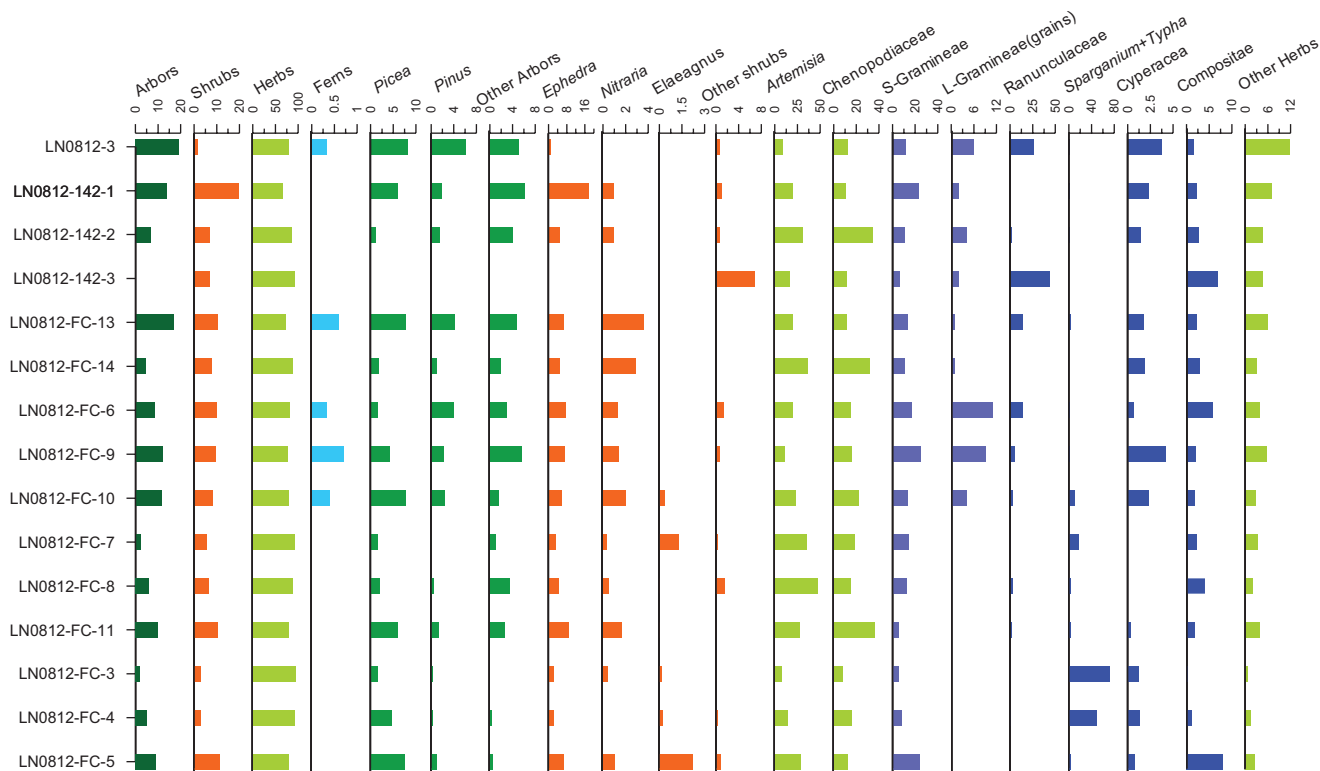
There are abundant historical remains left by ancient people in the farmland-like blocks. For example, a LC Han-Wei Dynastic tumulus is located at the centre of a ~10 ha block and a LD ruined farmhouse is located near a farmland-like block. Bronze arrowheads, treated jades and stoneware were found in some blocks during our field investigations.

The ground surface of the farmland-like blocks is covered by a gypseous incrustation layer (GIL) that consists of a series of horizontally bedded 1 mm thick gypsum-rich layers (Figure 3a,b,c). X-ray diffraction analysis identified quartz and gypsum as major minerals in the GIL. Gypseous incrustation on the surface consists of bowl-like stone pieces with tilted edges. The GIL is not present in the bottom of nearby canals. Owing to extremely low precipitation in the Lop Nur region, canals were mainly fed

by rivers. Because most main canals had been strongly wind-eroded after Loulan was abandoned and, in turn, lost the ability of water delivery, GIL and canals should be simultaneously formed during ancient Loulan kingdom period before the latest Yardang developed. In Yardang areas around GIL-covered blocks, gypseous deposition was not found in sediment formations of residual hillocks, such as in Loulan Pagoda sediment section.

In some farmland-like sites, GIL occurs at different heights as terraces. For example, there are three GIL terraces around the LC tumulus hillock and the altitude difference between two adjacent terraces is about 0.6~1 m. These features suggest that GIL is not a lacustrine or fluvial sediment but was formed associated with soil development.

At site No. 4 there is a ruined road that is 2~3.2 m wide, ~20 m long and 0.6 m high (Figure 3b) in a farmland-like block. The WNW direction of the ruined road is different from NE-extended Yardang hillocks. The flat top surface of the ruined road indicates an ancient ground surface. About 0.6 m height of the ruined road suggests that there was a ~0.6 m thick soil layer over the GIL but the soil layer had been wind-eroded in the latest Yardang development period. Thus, it is clear that GIL soil deposition is limited to farmland-like blocks. Because hard GIL is proof against wind-erosion, Yardangs did not develop further in farmland-like blocks after loose soil overlying on the GIL had been wind-eroded, in turn to form the flat surface of farmland-like blocks.



**Figure 4.** Pollen assemblages of soil samples from Loulan area. (Unit: %. S-Gramineae: pollen size  $<50\ \mu\text{m}$ . L-Gramineae: pollen size  $>50\ \mu\text{m}$  and unit is the number of grains.) Samples from farmlands: LN0812-3, LN0812-142-1~3, LN0812-FC-13 and 14 (site 3, 13 is from GIL and 14 is from the bottom of a canal), LN0812-6~10 (10 is from the foot of a ruined road in a farmland), LN0812-FC-11. Samples from other sites: LN0812-FC-3 ( $\text{N}40^{\circ}38'44.9''$ ,  $\text{E}90^{\circ}7'7.2''$ , LE ruined site), LN0812-FC-4 ( $\text{N}40^{\circ}35'42.3''$ ,  $\text{E}89^{\circ}57'25.3''$ ), LN0812-FC-5 ( $\text{N}40^{\circ}34'54.7''$ ,  $\text{E}89^{\circ}57'36.3''$ )

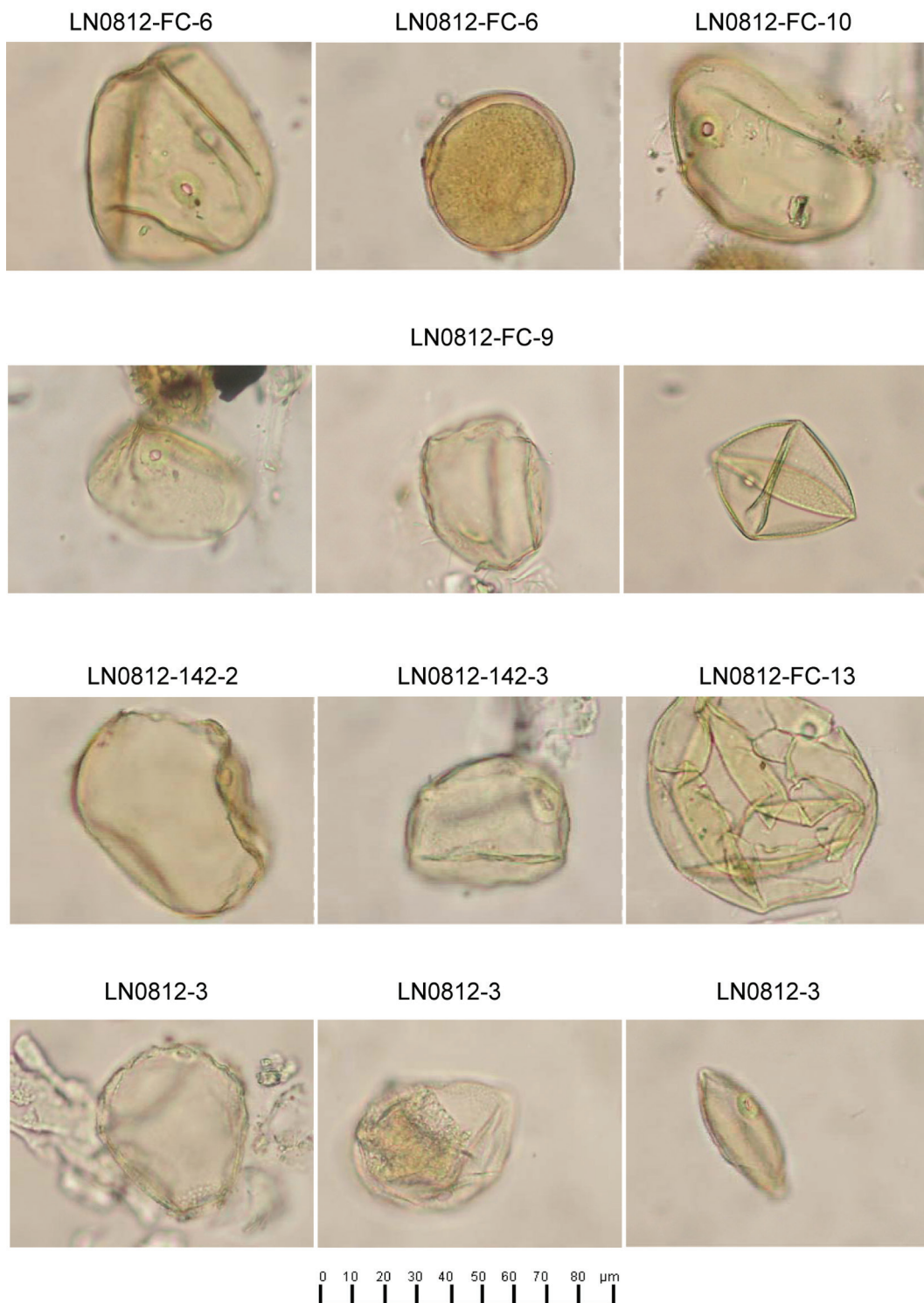
#### Pollen evidence from farmland-like blocks

Pollen assemblages of soil samples from GIL-covered blocks were analyzed (Figure 4). More than 40 pollen taxa were identified from the soil samples. Herbs are dominant in the assemblages and the percentage varied between 66% and 93%. Gramineae, Ranunculaceae, *Artemisia* and Chenopodiaceae are dominant taxa. Anthropogenic indicators such as *Urtica*, *Humulus* and local aquatic and marsh elements such as *Typha*, *Sparganium* and Cyperaceae are also present in pollen assemblages. Exotic taxa such as *Picea* and *Pinus* dominate arbors. *Ulmus* and *Juglans* also occur. *Ephedra* and *Nitria* were dominant shrubs. Few Ferns appear in the analyzed samples. Pollen concentrations of all samples are low and about 8–47 grains/g. The sum of *Artemisia* and Chenopodiaceae is only 14–35% of total pollen amount, suggesting that the ecological environment of the Loulan region was arid desert steppe in the ancient Loulan kingdom period. There was wetland near these sampling sites.

Gramineae pollen is extremely high and varies from 10% to 39%, which is close to modern farmland soil (Xu et al., 2007). Previous studies showed that the percentage of Gramineae pollen is usually low (Luo et al., 2007; Xu et al., 2007; Yan and Xu, 1989). The average Gramineae pollen is about 3.2% although the dominant vegetation is caespitose Poaceae and subshrub in Xinjiang desert steppe (Yan and Xu, 1989). Thus, it was believed that Gramineae pollen value may be more than 20% only in soil samples from farmland (Luo et al., 2007; Xu et al., 2007). In some soil samples from farmland-like blocks of Loulan areas, Gramineae pollen value is higher than 20%, strongly suggesting that these blocks are remains of ancient farmlands.

In order to distinguish between pollen from wild grasses and cultivated grasses, the biometric threshold generally used is that only pollen grains with a diameter above 37–45  $\mu\text{m}$  and with a protuberant annulus larger than 4–8  $\mu\text{m}$  are considered as Cerealia type grasses (Andersen, 1979; Joly et al., 2007). Joly et al. (2007) suggested another threshold according to 37 species of wild grasses and 4 species of Cerealia type grasses: 11  $\mu\text{m}$  for annulus diameter and 47  $\mu\text{m}$  for grain diameter. As doubts had been raised about the reliable separation of cereal pollen from those of large wild, coastal grasses (Arge, 1991), we gave these matters special attention. Gramineae pollen was well separated using a combination of size statistics and sculpturing. Measurements of all Gramineae pollen 45  $\mu\text{m}$  (long axis) and/or an annulus diameter (anl-D) of 8  $\mu\text{m}$  (measured in silicone oil) were chosen, i.e. anl-D  $>8\ \mu\text{m}$  and pollen size  $>45\ \mu\text{m}$  for cereal-type. Large (wild) Gramineae of anl-D  $>8\ \mu\text{m}$  or pollen size  $>45\ \mu\text{m}$  were not considered to be cereals, based on anl-D, sculpturing, and anl-D/pore diameter ratio. The criterion was applied in this study. In most soil samples from farmland-like blocks of Loulan, pollens with both a size  $>45\ \mu\text{m}$  and an annulus diameter  $>8\ \mu\text{m}$  were found. On the contrary, big pollen grains of cultivated grasses were not found in soil samples away from farmland-like blocks. Figure 5 shows the typical big pollen grains of cultivated grasses.

The percentage of large-sized pollen of LN0812-FC-6 and 9 from site No. 4 is 3.6% and 6.4%. In LN0812-142-1, 2, 3 of site No. 2, grains of large-sized pollens of cultivated grasses are also identified. In two soil sections of LN0812-142-1~3 and LN0812-FC-6~10, it was noticed that the numbers of large-sized pollen of samples from the lower soil is obviously less than that from upper soil. Particularly, both the total pollen amount and concentration of Poaceae are extremely low in LN0812-142-3 from silty sandy



**Figure 5.** Microphotos of typical large-sized pollens of cultivated grasses

sediment. This means that large-sized pollen grains in soil were dominated by the leaching process from up downwards in the soil profile.

Researchers have revealed that some pollen taxa, such as *Urtica*, *Humulus*, *Cyperaceae*, *Plantago*, etc. often occur at sites impacted by human activity (Hjllle, 1999; Li et al., 2003, 2008). In the analyzed soil samples, *Urtica* and *Humulus* were found in samples from upper soil of sites No. 1, 2, and 4, implying that there was intense human activity in these farmland-like blocks. These observations demonstrate that the GIL-covered blocks are ruined farmlands of the ancient Loulan kingdom and the type of

plant in the period was the typical cultivated grass of oasis near wetland. Large-sized pollen grains in samples from lower GIL soil came from upper cultivated soil because of leaching. At site Nos 1, 2 and 4, the pollen of *Vitaceae* was found, suggesting that *Vitaceae* had also been planted in the ancient Loulan kingdom.

## Discussion

### Formation of GIL

It is known that a soil profile consisted of two horizons, A and B (Hillel, 1998). The A horizon is the zone of eluviation at the upper

part of a soil profile influenced by strong leaching. The B horizon is the zone of illuviation at the lower part of a soil profile. In the extreme arid Xinjiang area, sulphate is more easily leached than carbonate in a soil profile because of low precipitation and strong evaporation (Li et al., 1983). It was noticed that glauberite is the major mineral that accumulated potassium-rich salt brine in sediments of Lop Nur (Wang et al., 2006) and gypsum is one of the major minerals of the salt-incrusted bed of dried Lop Nur (Xia et al., 2007). Modern observations also show that the major water chemistry of the local rivers is of Ca-Mg-SO<sub>4</sub> in Tarim basin (Lu, 1993). Because of extremely low precipitation in Lop Nur, the amount of rainfall is deficient to leach saline minerals from the soil profile. It was noted that there are canals near or within all farmland-like blocks, suggesting that rivers were the major source of irrigation water of farmlands. The irrigation water infiltrated downwards in soil of the farmlands, leading to the gypseous deposition at soil horizon B. After these farmlands were abandoned, horizon A of the cultivated soil layer was strongly wind-eroded because of its loose nature. After horizon B was exposed, the development of Yardang landforms lessened to form the flat ground surface because the hard GIL resisted further wind erosion. Therefore, we suggest that the GIL in the blocks represents a ruined soil horizon B. Horizon A of the 0.3–0.6 m thick cultivated layer had been wind-eroded in most cases but a few Horizon A layers still remained in some places.

#### Historical records and age of farmlands

Environment, agricultural production and lifestyle of the Loulan kingdom were documented in many Chinese historical records. Hanshu (Ban, 92) stated that the primary name of the Shanshan kingdom was Loulan, whose capital was Yuni city, and there were 1570 families and about 14 100 people. After the third century, Loulan was gradually obsolete as the army of the Former Liang Dynasty of China retreated back to Central China (Xia et al., 2007; Zhang, 2001). Faxian (i.e. Fahsien) (416), a Chinese pilgrim monk of Eastern Jin Dynasty who travelled to India from AD 399 to 412, stayed about a month in Shanshan in AD 399. He described the kingdom as 'rugged and hilly, with a thin and barren soil. ... There might be in the country more than four thousand monks' in his book *Foguoji*. The last literal record was in the Monk Xuanzang's book *Datangxiyuji* of the Chinese Tang Dynasty in about AD 645. He said that he passed through the ancient Nafubo kingdom, i.e. Loulan (Xuanzang, 645). 'Nafubo' is a pronunciation similar to 'Lop Nur' in Chinese. After that, Loulan completely disappeared from Chinese historical records for about 1500 years.

Wooden tablets found in Loulan indicated that cultivation and irrigation lasted at least to AD 330 (Xia et al., 2007). Historical records show that the reduction of soldiers' grain ration and the deficiency of irrigation water took place in succession after about AD 270 (Xia et al., 2007; Zhang, 2001). It suggests that water quantity of the Zhubing River decreased markedly after AD ~270, which resulted in the retreat of Former Liang's army from Loulan. The monk of Tang Dynasty, Xuanzang, passed through the abandoned kingdom in about AD 645 (Xuanzang, 645), implying that the kingdom lasted a few hundred years after Former Liang's army left. The kingdom must have completely disappeared after Xuanzang's visit. Therefore, Loulan farmlands should be abandoned at least before 1640–1365 (about 1500) years.

#### Scale of farmland and its implication

Remotely sensed images reveal that the total area of farmland in the west bank of Lop Nur was immense. Incomplete statistics show that the total area of farmland was more than 5000 ha, i.e. enough to support a strong country with tens of thousands of people, although these farmlands may have been cultivated at different times. There are only more than 30 000 people in Ruoqiang County at present. Thus, the ancient Loulan kingdom was once particularly prosperous on account of the level of agricultural technology at the time. The huge scale of farmlands suggests that farmlands should have been cultivated by organized armies or landlords, not individual families. The 10–30 cm thickness of GIL implies that the history of farmland irrigation lasted for a long time, at least hundreds years, in turn to support the prosperity of ancient Loulan kingdom over 400 years. Pollen records suggest that crops such as grapes might have been planted in addition to grains.

Comb-like canals and rivulet-like canals may have been used to irrigate different vegetation or developed by different crowds or during different periods. All the above facts suggest that the irrigation techniques of the Loulan kingdom were well-developed, although cultivation grain types had been unclear. Undoubtedly, the cultivation and irrigation techniques of Loulan kingdom were mostly developed throughout the Tarim Basin and even Central Asia during the period. However, crop grains found in Xiaohe tumulus suggest that cultivation agriculture already existed as early as 2000–1450 BC (Xia et al., 2007). Thus, large-scale cultivation and irrigation in the Loulan kingdom may have begun by Han's troops, as recorded in historical literature, but the inception of farming should be even earlier.

The above discovery also means that the water flow of rivers was plentiful enough to support well-developed irrigation agriculture in the early and mid period of the Loulan kingdom. Thus, another wet and water-rich period after the about 4 ka arid event was from at least 80 BC (the beginning of farming practiced by Han's troops) to about AD 300 (Former Liang's troop leaving). On the other hand, the increasing shortage of water during the late period of the Loulan kingdom was one of the direct factors that lead to the decline of irrigation agriculture, in turn finally forcing Former Liang's troops to leave. This implies that modern dunes of the Lop desert and the Takalamagan desert may have rapidly developed over the last 1500 years, along with the formation of the latest Yardang in the Loulan area.

#### Conclusion

Several new lines of evidence retrieved from the Loulan area indicate that there is a large area of farmland ruins of the ancient Loulan kingdom, at least about 5000 ha, in the west bank of Lop Nur. Regular and straight boundaries, crossed canals, covered GIL, and large-sized pollen of cultivated grass in GIL samples are major features of farmlands. The upper cultivated soil layer overlaid on GIL, i.e. soil horizon A, had often been wind-eroded and GIL is the ruined soil horizon B. These new discoveries suggest that the agriculture of the ancient Loulan kingdom was well-developed. The huge scale and area of farmlands and the GIL thickness suggest that the irrigation history of farmland lasted for a long time. Fluvial and lacustrine sediments in the Loulan area deposited during the 4–8 ka BP period, represented that wet Holocene optimum and two arid events of ~4 and ~8 ka BP took place in the westerlies-dominated area. The Loulan kingdom must have developed during a relatively wet stage and the ecological



environment was typical of cultivated grass of oasis near wetland. The shortage of water during the late period of the Loulan kingdom led to the decline of irrigation agriculture and finally the collapse of the kingdom.

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