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Ancient landslide-dam events in the Jishi Gorge, upper Yellow River valley, China

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ABSTRACT

Some scholars have argued that the formation and outburst of an ancient dammed lake in the Jishi Gorge at ca. 3700 cal yr BP resulted in the destruction of Lajia, the site of a famous prehistoric disaster in the Guanting Basin, upper Yellow River valley, China. However, the cause of the dammed lake and the exact age of the dam breaching are still debated. We investigated ancient landslides and evidence for the dammed lake in the Jishi Gorge, including dating of soil from the shear zone of an ancient landslide, sediments of the ancient dammed lake, and loess above lacustrine sediments using radiocarbon and optically stimulated luminescence (OSL) dating methods. Six radiocarbon dates and two OSL dates suggested that the ancient landslides and dammed lake events in the Jishi Gorge probably occurred around 8100 cal yr BP, and the ancient dammed lake was breached between 6780 cal yr BP and 5750 cal yr BP. Hence, the outburst of the ancient dammed lake in the Jishi Gorge was unrelated to the ruin of the Lajia site, but likely resulted in flood disasters in the Guanting Basin around 6500 cal yr BP.

Introduction

It has been suggested that natural hazards are one of the most important factors behind the collapse of prehistoric cultures. For example, the disappearance of the pre-Columbian Mayan civilization in Central America is said to have been induced by severe drought events (Haug et al., 2003; Kennett et al., 2012). Hazards characterized by a sudden onset, including earthquakes, volcanoes, landslides and floods, have caused the ruins of ancient cities or settlements, such as Pompeii. Such disaster sites are important for studying daily lives and human–land relations in ancient times, as these sites are often well preserved by the rapid deposition of sediment above them.

The Lajia site in the upper Yellow River valley, northwest China, destroyed by natural hazards around 3700 cal yr BP (Yang et al., 2003), was labeled as one of the ten most significant Chinese archeological discoveries in 2002. The Lajia site provides not only valuable, well-preserved evidence for archeological studies, such as the earliest millet noodles in the world (Lu et al., 2005), but it also provides a good opportunity for multi-disciplinary research. The processes and mechanisms of the natural hazards which destroyed the Lajia site have provoked intense interest in scientists from different disciplines (especially geologists and archeologists), resulting in concentrated study and discussion in recent years (Yang et al., 2003, 2004, 2005; Wu et al., 2009; Zhang et al., 2009; Hou et al., 2012; Ma et al., 2012). Although scholars have agreed that the Lajia site was ruined by earthquakes and paleofloods which affected the Guanting Basin during the Qijia period (4100–3600 cal yr BP), the causes and processes of these prehistoric disasters still remain unclear and debatable.

Some scholars argued that the paleofloods in the Guanting Basin were induced by the breaching of a lake at the Jishi Gorge dammed by a paleo-landslide (Fig. 1) during the mid-Holocene, and the driving forces of the disasters in the Basin were not climate change but tectonic events (Wu et al., 2009). The argument is interesting, for the outburst of dammed lakes might indeed result in huge floods (Montgomery et al., 2004; Kochel et al., 2009) and the consequent destruction of human societies located downstream (Lliboutry et al., 1977). However, such an argument contradicts the evidence that paleoflood events in the Guanting Basin occurred many times instead of once during 3650–2750 cal yr BP (Yang et al., 2005), and indeed that paleofloods occurred prior to the Qijia settlement at the Lajia site: as suggested by excavations of the site (Ye, 2008), a Qijia cultural layer was found embedded in the paleoflood sediments. Those paleoflood sediments may have formed in the Guanting Basin before 6500 cal yr BP (Ma et al., 2012). Moreover, the ages of the ancient dammed lake may be unreliable, for the published radiocarbon dates are not directly derived from its sediment (Wu et al., 2009).

The chronology of ancient landslide-dam events can be determined by radiocarbon dating and OSL dating of the remains of landslides and dammed lake sediments if those dating samples are properly selected

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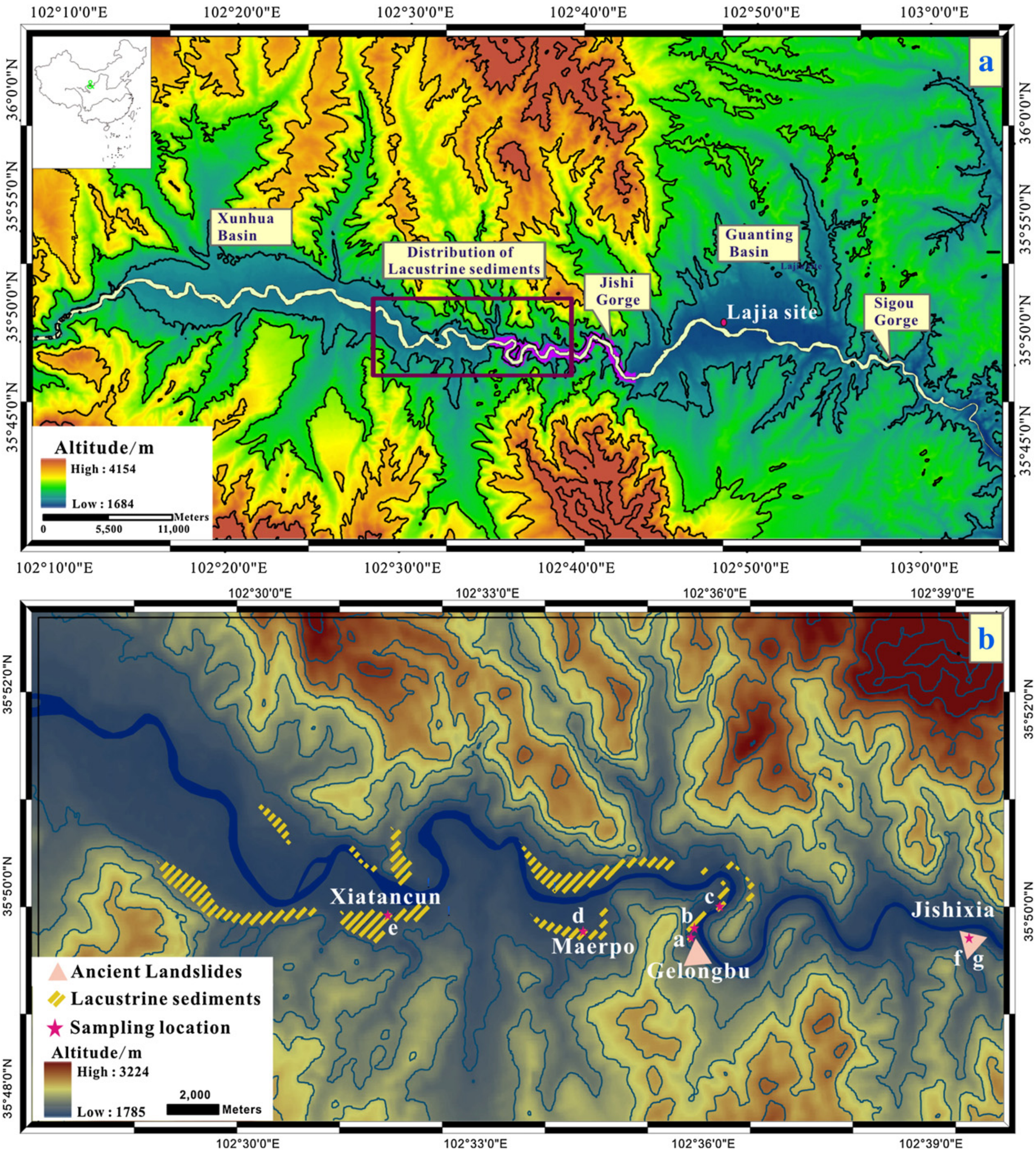

Figure 1. Location of the study area. a. The locations of the Xunhua Basin, the Jishi Gorge, the Guanting Basin and the Sigou Gorge; b. The distribution of ancient landslides, lacustrine sediments and sampling sites mentioned in the text.

(Pánek et al., 2010; Wang et al., 2011). Here, we present the results from radiocarbon dating and OSL dating of the ancient dammed lake sediment and ancient landslides in the Jishi Gorge on the basis of detailed field investigation. We aim to determine the ages of the ancient landslides and dammed-lake event in the Jishi Gorge, and to examine its relation to the ruin of the Lajia site and paleoflood disasters in the Guanting Basin. We also tried to determine the ages of ancient landslides by radiocarbon dating the soils of shear zones found in ancient landslides, and to test the reliability of these results through comparison with the radiocarbon dates taken from the bottom of ancient dammed lake sediments in the Jishi Gorge. This potentially provides a new insight into the study of the ages of ancient landslide events.

Study area

The Jishi Gorge is located in Xunhua County, Qinghai Province, China. It is about 25 km west of the Lajia site (Fig. 1a). Here, the Yellow River flows through the Jishi Gorge from west to east. The Jishi Gorge is a steep, narrow V-shaped valley between Guanting Basin in its lower reaches and Xunhua Basin in its upper reaches (Fig. 1a). The gorge is surrounded by the Laji Mountains to the northwest, and the Jishi Mountains to the south.

This region is currently dominated by a semiarid alpine climate, with long periods of freezing during winter and warm sunshine in the summer, resulting in substantial variations in annual temperature. Based on records taken from the Xunhua County weather station from 1956 to 2000, mean annual temperature is 8.5°C. Daily mean temperature ranges from 34.1°C in July to −19.9°C in January. Mean annual precipitation is 266.1 mm with considerable inter-annual variability, and mean annual potential evaporation is as great as 2189.4 mm. Up to 50–80% of the annual precipitation falls from June to August.

The lower series of the Cretaceous Hekou Formation (K_1), which is widely exposed on both sides of the valley, comprise mainly conglomerates, sandstones, and pebbly sandstones intercalated with mudstones and siltstones. Quaternary loess covers part of the slopes (NHSDI, 1991; Peng et al., 1997). Although there are a few small-scale folds and joints, the main structural features are small-scale faults (NHSDI, 1991; Peng et al., 1997). The area is classified as a weakly seismic zone in China (NHSDI, 1991), although a number of earthquakes up to M 6 have been recorded within 100 km (Liu et al., 2003). A paleoearthquake that occurred ca. 3500 yr ago, for example, resulted in the destruction of the Lajia village (Yang et al., 2003).

The area has experienced many large ancient rockslides, two of which were used in this research. One is located at the great bend (located at Gelongbu) in the Jishi Gorge and resulted in the formation of extensive lacustrine sediment deposition upstream (Figs. 1, 2), overlying detrital material and large gravel beds. Those lacustrine sediments extend about 30 km upstream to the outskirts of Xunhua City (Figs. 1, 2). The other rockslide is located about 600 m downstream of the Jishi Gorge reservoir dam, and about 15 km downstream of the great bend in the Jishi Gorge (Fig. 1). This landslide has been termed the Jishixia Landslide, with two long exploration adits used during previous engineering studies extending into its shear zone (Zhang et al., 2010). The adits thus provided a rare opportunity to collect soil samples from a landslide shear zone. These samples were used in subsequent radiocarbon dating to determine the age of the ancient landslide.

Materials and methods

We investigated the strata of the lacustrine sediments and the shear zone of the landslide. Four different sites – Ma'erpo, Xiatancun, Gelongbu and the Jishixia Landslide (Fig. 1b) – were selected for the collection of samples for dating. Two bulk organic matter samples were obtained from the base of the lacustrine sediments at the Gelongbu and Xiatancun sites for radiocarbon dating (Figs. 1b, 3c, e), and two samples were collected for OSL dating from the upper part of the lacustrine sediments at the Ma'erpo site, which are more than 30 m thick (Figs. 1b, 3d). Additionally, two bulk organic matter samples were collected from the upper lacustrine sediments and from the base of the overlying loess at Gelongbu for radiocarbon dating (Figs. 3a, b), and two bulk organic matter samples were obtained from the shear zone of the Jishixia Landslide (Figs. 1b, 3f, g).

Four bulk organic matter samples were dated using the benzene method and liquid scintillation counting at the Key Laboratory of Western China's Environmental Systems (Ministry of Education), Lanzhou University, and two bulk organic matter samples were dated using the benzene method and liquid scintillation counting at the State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, CAS (Table 1). The IntCal09 curve (Reimer et al., 2009) and the Libby half-life of 5568 yr were used in the calculation of all dates, with the calibration performed using the Calib V. 6.0.1 program (Stuiver and Reimer, 1993). All ages reported are relative to AD 1950 and referred to as "cal yr BP".

Luminescent signals were measured in the Risø-TL/OSL-20 reader at the Key Laboratory of Western China's Environmental Systems, Lanzhou University. By using the routine method for mineral isolation (Zhao and Li., 2002), we isolated quartz fractions within the ranges of 38–63 and 63–90 μm. Small aliquots were prepared by mounting quartz grains into 2 mm diameter areas of stainless steel disks using silicon oil. The

Figure 2. Photographs of ancient landslides and lacustrine sediments in the Jishi Gorge. a. The junction between ancient landslide and lacustrine sediments at the Gelongbu site; b. Gelongbu Landslide. The dashed line represents the main scarp of the landslide; c. Lacustrine sediments along the banks of the Yellow River.

Figure 3. The sampling sites and dates of lacustrine sediments and ancient landslides in the Jishi Gorge.

double SAR protocol (Banerjee et al., 2001) was used to measure the post-IR blue OSL signals from quartz minerals with the aim of eliminating any potential influence of possible contamination of K-feldspar.

Only those aliquots satisfying the following criteria were involved in statistical data analysis: (1) where IRSL signals are negligible compared with OSL signals; (2) where the recycling ratio is between 0.9 and 1.1; and (3) where recuperative OSL signals are weaker than 5% of the natural OSL signal. To improve the precision of De values, we calculated the weighted mean De values and errors from each sample based on each qualified aliquot referring to Thomsen et al. (2007), with weights equal to the reciprocals of the square values of relative standard deviation (RSD) for each measurement.

The content of U, Th and K was measured using Instrumental Neutron Active Analysis (INAA). The dose rate was obtained by calculating contributions from cosmic rays and from the elements U, Th and K (Aitken, 1985). Considering the potential influence of uncertainty in the water content to dose rate, we measured water content from both natural samples and saturated samples. We calculated OSL ages on the basis of two different scenarios, natural (based on evaluated water content) and saturated (based on saturated water content) by using the newly updated program AGE.EXE (Grün, 2009).

Table 1
Calibrated radiocarbon dates of sediments in the Jishi Gorge.

Lab number	Sampling position	Dating material	Radiocarbon date (^{14}C yr BP)	Calibrated age (cal yr BP, 1σ)
KF0812027[a]	Landslide slip zone	Bulk organic matter	7872 ± 65	8681 ± 97
KF0812026[a]	Landslide slip zone	Bulk organic matter	7362 ± 50	8177 ± 125
LUG09-17[b]	Bottom of lacustrine sediment	Bulk organic matter	7234 ± 94	8067 ± 95
LUG09-65[b]	Bottom of lacustrine sediment	Bulk organic matter	6121 ± 71	7035 ± 121
LUG08-105[b]	Bottom of loess above lacustrine sediment	Bulk organic matter	4986 ± 72	5748 ± 131
LUG4-07[b]	Upper lacustrine sediment	Bulk organic matter	5936 ± 94	6775 ± 112

Superscripts:
[a] Nanjing Institute of Geography and Limnology, CAS.
[b] Lanzhou University.

Results

Lacustrine sediments in the Jishi Gorge region primarily consisted of bluish-yellow silty clays with obvious horizontal bedding. At some sites such as Gelongbu and Ma'erpo, these sediments are tens of meters thick. Many horizontal red clay layers were found inter-bedded within lacustrine sediments. These lacustrine sediments are mainly distributed on the second terrace of the Yellow River, which is about 10 m above the present river bed. A coarse gravel layer was exposed at the front of the second terrace (Fig. 3c), overlain by lacustrine sediments.

The radiocarbon dates from the lowest strata of lacustrine sediments at the Gelongbu and Xiatancun sites are 8067 ± 95 cal yr BP and 7035 ± 121 cal yr BP (Figs. 3c, e; Table 1). The sample from the upper lacustrine sediment at Gelongbu, which was collected about 1.7 m below the top of the sediment, was dated to 6775 ± 112 cal yr BP (Fig. 3b; Table 1). At the Ma'erpo site, lacustrine sediments are more than 30 m thick, with their base being unexposed. A 40 cm thick sand–gravel layer was found within the lacustrine sediments, with most gravels being finer than 5 cm in diameter. The two OSL dates of the lacustrine sediments above this sand–gravel layer are 5.38 ± 0.45 ka and 5.87 ± 0.5 ka (Fig. 3d; Table 2).

At the Gelongbu site, which is at the junction between ancient landslide and lacustrine sediments (Fig. 2a), sediments are as much as approximately 50 m thick. A 50 cm thick loess layer was found overlying the lacustrine sediments and its base was dated to 5748 ± 131 cal yr BP (Fig. 3a; Table 1).

The Jishixia Landslide has three different shear zones located in the adit at horizontal depths of 72 m (H_1), 112 m (H_2), and 118 m (H_3). The samples taken from the shear zone at 72 m and 112 m were dated to 8177 ± 125 cal yr BP and 8681 ± 97 cal yr BP (Figs. 3f, g; Table 1). Unfortunately, the age of the shear zone at 118 m was not acquired.

Discussion

Large ancient landslides occurred in the Jishi Gorge, as indicated by the deposits of landslides in the region (Fig. 2). These ancient landslides originated during the Pleistocene or earlier under different geomorphic and climatic conditions than are present today, and they are now inactive. They generally present particular geomorphic features (McCalpin, 1984; González-Díez et al., 1999). Inactive ancient landslides present considerable hazards through their potential reactivation. The movement of most landslides occurs along a discrete shear surface or zone (Lambe and Whitman, 1969). Hence the shear zone can provide a direct dating of such movement. Based on the dating results from the shear zones studied (Figs. 3f, g; Table 1), ancient landslides events in the Jishi Gorge might have occurred between 8700 and 8200 cal yr BP. Our results are roughly consistent with those obtained by Peng et al. (1997) and Zhang et al. (2013). They dated the lacustrine sediments (8500 ± 400 cal yr BP, 9016 ± 425 cal yr BP and 7984 ± 334 cal yr BP) at the Gelongbu dammed lake using radiocarbon dating, and concluded that these landslides may have occurred during the period 9000–8000 cal yr BP.

The lacustrine sediments in the Jishi Gorge region were deposited within a huge ancient dammed lake, which was induced by the blockage of the Gorge by the aforementioned ancient landslides (Fig. 2a). Huge landslide-dammed lakes have also been formed in China in recent times, such as those in Wenchuan County, Sichuan Province, China, which were induced by the 2008 *Ms* 8.0 Wenchuan earthquake (Hsu and Hsu., 2009; Yin et al., 2011; Cui et al., 2012). The lacustrine sediments in the Jishi Gorge region mainly consist of horizontally bedded, bluish-yellow silty clays. Plenty of horizontal red clay layers were found inter-bedded within those lacustrine sediments. These clay layers were probably formed by the superimposed effects of local runoff and the main channel of the Yellow River, which eroded and then transported the Pliocene red clay that is widely distributed in the valleys of the upper Yellow River. The suspended red clay might have been deposited between the formation and breach of the ancient dammed lake in the Jishi Gorge. The formation and evolution of the ancient dammed lake were complicated, as indicated by the sand–gravel layer within the lacustrine sediments at the Ma'erpo site. This layer was probably formed by strong currents when the dammed lake was still extant.

Radiocarbon dating of bulk organic matter at the base of lacustrine sediments could indicate the age of the formation of the ancient dammed lake; that from the Gelongbu site was dated to ca. 8100 cal yr BP (Figs. 1b, 3c) and that from the Xiatancun site to ca. 7000 cal yr BP (Fig. 3e). The ancient dammed lake in the Jishi Gorge might have formed soon after some landslide events, and if this is the case it would follow that the ages of the bulk organic matter at the base of the lacustrine sediments and the ancient landslide shear zone should be approximately the same. Two of those three radiocarbon dates overlapped at around 8100 cal yr BP (Fig. 4), suggesting that the ancient landslides and subsequent formation of a dammed lake in the Jishi Gorge probably occurred at that time. The other dating (8681 ± 97 cal yr BP) of soils in the landslide shear zone is older than those events, and is probably due to the admixture of old sediments. Large

Table 2
OSL dating results of lacustrine sediment at Ma'erpo location.

Lab code	Sample (elevation 1859 m asl)	Depth (m)	Water content (wt.%)[a]	K (%)	Th (ppm)	U (ppm)	Cosmic ray dose rate (Gy/ka)	Total dose rate (Gy/la)	Grain size (μm)	D_e (Gy)	Aliquots	Age (ka, ±1σ)
LZU0912	Mep090329	7	1.14 (20 ± 5)	1.83 ± 0.04	11.20 ± 0.32	2.43 ± 0.09	0.12	2.83 ± 0.16	63–90	15.22 ± 0.92	16	5.38 ± 0.45
LZU0913	Mep090329-2	7.2	1.05 (20 ± 5)	1.72 ± 0.04	9.80 ± 0.29	2.14 ± 0.08	0.12	2.60 ± 0.23	38–63	15.29 ± 0.80	12	5.87 ± 0.59

Note:
[a] The evaluated water content (the number in the parentheses in this column) was used in the dose rate calibration.

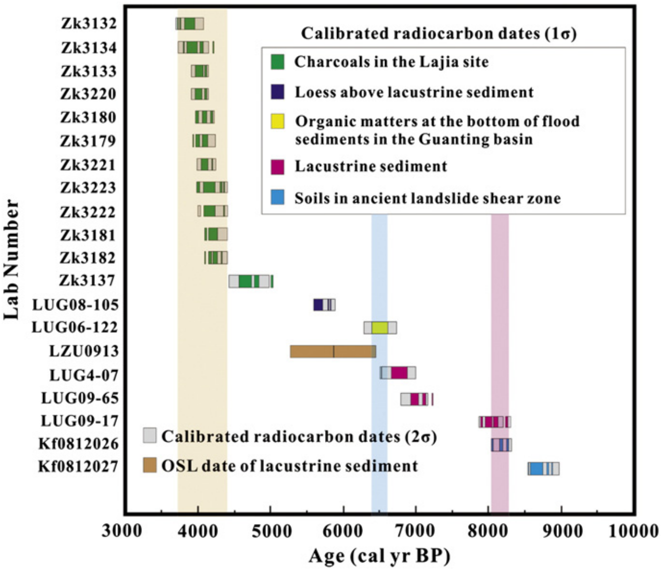

Figure 4. Radiocarbon (uncalibrated: black) and OSL dating bars. The vertical pastel purple and blue bars suggest respectively the ages of the formation and extinction of the ancient landslide-dammed lake in the Jishi Gorge; the vertical pastel red bar shows the ages of the Qijia settlement at the Lajia site.
Radiocarbon dates for the Lajia site and LUG06-122 were reported by IA, CASS (2003, 2005) and Ma et al. (2012).

deep-seated landslides typically occur during a wetter climatic cycle or during earthquake episodes (Takagi et al., 2007; Jakob and Lambert, 2009; Yin et al., 2010; Schulz et al., 2012); this suggests that considerable climatic fluctuations (accompanied by intensive rainfall) and/or tectonic events occurred in this area during the early Holocene. Previous results from limit-equilibrium analyses of two ancient landslides in the Jishi Gorge (Dong, 2008; Zhang et al., 2010) suggest that earthquakes would more easily trigger the formation of large deep-seated landslides, although more evidence from ancient earthquake studies of this area are needed to support this hypothesis. Climate change might be another possible factor that induced the ancient landslide event in the Jishi Gorge because temperature and precipitation fluctuated drastically around 8200 cal yr BP in east Qinghai Province, as recorded by pollen and redness found within Qinghai Lake sediments (Liu et al., 2002; Ji et al., 2005). The 8200 ka climate event was also widely reported in many other parts of the world (Alley et al., 1997; Rohling and Pälike, 2005).

The radiocarbon dating (7035 ± 121 cal yr BP) of the bulk organic matter at the base of the lacustrine sediments at the Xiatancun site might deviate from the age of those landslide-dammed lake formation events due to the erosion of ancient lake sediments by local runoff or by the Yellow River. The Xiatancun site is about 20 km from the ancient lake dam at Gelongbu, and the river bed of the Yellow River at the Xiatancun site is about 15 m higher than that at the Gelongbu site. Sediments from the ancient dammed lake at the Xiatancun site could therefore have been exposed and so become susceptible to erosion by the variable flow of the Yellow River before the lake breach.

According to the radiocarbon dating of the loess overlying the lacustrine sediment and that of the upper lacustrine sediment at the Gelongbu site (Figs. 3a, b; Table 1), the ancient dammed lake had disappeared between 6780 and 5750 cal yr BP, for the loess was deposited after the exposure and consolidation of the remains of the ancient dammed lake. It has been suggested by Wu et al. (2009) that the water volume of the ancient dammed lake in Jishi Gorge was 11.71×10^8 m^3, hence the outburst of the ancient dammed lake might have brought huge quantities of sediments and flux downstream to the Guanting Basin, resulting in major flood disasters in the Basin. The outlet of the Guanting Basin is located at the western end of the Sigou Gorge (Fig. 1a), which is a deep, steep, narrow, V-shaped, 40 km long valley. The huge discharge of sediments might have blocked the outlet of the Guanting Basin, raised the bed of the Yellow River and induced floods in the Basin. The radiocarbon dating of organic matter at the base of paleoflood sediments in the Guanting Basin (LUG 06–122) suggests that the first paleofloods there during the Holocene occurred around 6500 cal yr BP (Ma et al., 2012), and the outburst of the ancient dammed lake in the Jishi Gorge also likely to have occurred at about the same time (Fig. 4). Radiocarbon dating of lacustrine sediments indicates that the ancient dammed lake in the Jishi Gorge did not burst before 6780 cal yr BP, whereas two OSL dates of lacustrine sediments at the Ma'erpo site partly overlap the LUG 06–122 date (Fig. 4). These dates suggest that the ancient dammed lake likely burst synchronously with the first flood disaster during the Holocene in the Guanting Basin downstream, although they can only provide a chronological framework.

Wu et al. (2009) argued that the ancient landslide events and the formation and outburst of the dammed lake in the Jishi Gorge occurred around 3680 cal yr BP, and that this was what destroyed the Lajia site in the Guanting Basin. However, our study suggests that the ancient landslides and dammed lake in the area emerged around 8100 cal yr BP. The ancient dammed lake in the Jishi Gorge had disappeared before 5750 cal yr BP, which is much earlier than the period of the Qijia settlement at the Lajia site (4270–3850 cal yr BP, IA, CASS, 2003, 2005). This suggests that its outburst was not the cause of the collapse of the Lajia site (Fig. 4). Wu et al. (2009) argued that the ancient landslide dam was quickly overflowed by the water level of the Yellow River after its blockage and that the dammed lake burst several days later. However, the ancient dammed lake developed by the Gelongbu Landslide and other landslides in the Jishi Gorge might have persisted for a long period. Judging from the deposits and boreholes and pits, the landslide dam had a length of 1.0 km at the crest and 1.5 km at river level, with a height of approximately 200 m. In addition, lacustrine sediments show that the reservoir behind the landslide dam was about 33 km long along the main valley (NHSDI, 1991; Peng et al., 1997). At many sites (such as the sites at Ma'erpo and Gelongbu), thousands of horizontal beds of lacustrine sediment can be observed. Some scholars have calculated that these lacustrine beds have an average thickness of 1 m and have speculated upon the number of years required for their formation (Peng et al., 1997; Zhou et al., 2009). They have inferred that the ancient dammed lake might have existed for about 1000 yr according to the stratigraphic record. Many other studies have also indicated that ancient landslide-dammed lakes can be very stable and last for centuries or even millennia (Reneau and Dethier., 1996; Hermanns et al., 2004; Korup et al., 2006). We propose that the ancient landslides and dammed lake events had no effect on the destruction of the Lajia site, because the dammed lake failed at least 2000 yr prior to its abandonment (Fig. 4).

Conclusion

Ancient landslide events occurred in the Jishi Gorge in the upper Yellow River valley, and resulted in the formation of a huge ancient dammed lake around 8100 cal yr BP. Widespread lacustrine sediments then formed along the river valley upstream from the dam. The ancient dammed lake was breached between 6780 cal yr BP and 5750 cal yr BP, this outburst being unrelated to earthquake activity and the destruction of the Lajia site during the Qijia period, but probably resulting in the first paleoflood in the Guanting Basin around 6500 cal yr BP. The radiocarbon dating of soils comprising ancient landslide shear zones roughly corresponds with those of sediments from the ancient dammed lake, suggesting shear zone dating may be used to determine the ages of ancient landslides. This hypothesis should be further tested by future research.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.yqres.2013.09.003.

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