Quaternary Research 86 (2016) 316–325

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: http://www.journals.elsevier.com/quaternary-research

Chronology of newly-discovered Paleolithic artifact assemblages in Lantian (Shaanxi province), central China

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ARTICLE INFO

Article history:
Received 26 April 2016
Available online 20 October 2016

Keywords:
Lithic artifacts
Loess-paleosol sequence
Bahe River
OSL dating
Magnetostratigraphy
Central China

ABSTRACT

The *Homo erectus* cranium, mandible and hundreds of associated lithic artifacts found in Lantian (central China) in the 1960s demonstrate that the area was important for hominin habitation during the early to middle Pleistocene. However, the region, which was not adequately researched until the early 2000s, still poses several questions regarding hominin behavior and lithic technology development. In this study, three loess-paleosol sequences (the Jijiawan, Ganyu and Diaozhai sites), from which *in situ* stone artifacts were recovered, are investigated and dated by optically stimulated luminescence (OSL), magnetostratigraphy and stratigraphic correlation. The results demonstrate that the artifacts are located within paleosol layers S4 (correlative with marine oxygen isotope stage (MIS) 11), S3 (MIS 9), S2 (MIS 7), and S1 (MIS 5); and within loess layer L1 (MIS 2–4). The main stone-knapping technique used was direct hard hammer percussion. In addition, the technological features of the stone tools found at these sites exhibit little variation, indicating the presence of a long-established, stable technology in the Lantian area. Our observations show that the ancient humans lived episodically on the terraces of the Bahe River from the early Pleistocene, indicating a long history of hominin occupation of the region.

Introduction

The discovery in the 1960s of a mandible and cranium of *Homo erectus* at the Chenjiawo site and the Gongwangling site (Woo, 1964; Jia, 1965) in Lantian county, Shaanxi province, demonstrated that early hominins occupied this area of China. Preliminary paleomagnetic dating of the loess deposits within which the mandible and cranium were found indicated ages of about 0.65 Ma and 1.15 Ma (An and Ho, 1989). However, a recent magnetostratigraphic study suggests an age of the cranium of approximately 1.63 Ma (Zhu et al., 2015). These findings have greatly advanced our understanding of human evolution in East Asia during the early Pleistocene. In addition to the Chenjiawo and Gongwangling sites, approximately 30 other Paleolithic open-air sites and more than 3000 artifacts have been discovered within loess-paleosol deposits in the area by our research team. These finds provide valuable records of early human behavior and the technological features of the lithic technologies (Wang et al., 2014a). However, few artifacts have been found *in situ*, with most being collected from the ground surface and therefore with no age control. As a result, the ages of Lantian Paleolithic assemblages younger than the Lantian Man remain unclear, and further chronological studies are needed.

Magnetostratigraphic and optically stimulated luminescence (OSL) dating have been used successfully to date aeolian sedimentary sequences in the Eastern Qinling Mountains, central China (Lu et al., 2007, 2011a, 2011b; Sun et al., 2013, 2014). These sequences constitute a continuous terrestrial record of changing climatic conditions spanning the last 22 million years (Guo et al., 2002). According to the typical chronostratigraphic model for the Chinese loess sequences (Heller and Liu, 1982; Lu et al., 1999), the first loess layer (L1) and the first paleosol layer (S1) were deposited during the last glaciation and last interglaciation, respectively; and the second loess unit (L2) and the second paleosol unit (S2) were formed during the penultimate glacial and interglacial periods, and so on. This model can be applied to the Lantian area which is

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http://dx.doi.org/10.1016/j.yqres.2016.08.008
0033-5894/

located in the southern part of the Loess Plateau (Porter et al., 1992; Zheng et al., 1992), close to the loess sites in Eastern Qinling Mountains (Lu et al., 2011a, 2011b).

In the present study, we used magnetostratigraphic and OSL dating together with stratigraphic correlation to date three newly-discovered Paleolithic sites (the Jijiawan, Ganyu and Diaozhai sections) along the Bahe River (the same watershed within which the Gongwangling and Chenjiawo sites occur). Our primary goal was to constrain the age of the *in situ* artifacts. Subsequently we compared the ages and the lithic technologies of these artifacts with those of other sites in the vicinity of the Eastern Qinling Mountains in order to shed further light on the ancient human occupation of central China during the middle to late Pleistocene.

Study sites

Lantian county, on the northern flank of the Qinling Mountains, is situated in the southern part of the Chinese Loess Plateau and is drained by the Bahe River (34°07′–34°17′N, 109°07′–109°32′E). The Bahe River is a tributary of the Weihe River which flows into the Weihe Basin, eventually joining the Yellow River (Fig. 1). Within this region the elevation of the Bahe River ranges from 820 m to 440 m and its fluvial terraces and drainage divides are mantled by thick loess-paleosol deposits (Porter et al., 1992; Wu et al., 2013).

The Jijiawan section (34°16.5′N, 109°15′E) is at an elevation of 930 m above sea level (asl) and lies 500 m above Bahe River (Figs. 1 and 2). The Ganyu section (34°14.6′N, 109°10.2′E) is located on the third terrace of Bahe River at an elevation of 532 m asl and is 112 m above the river (Figs. 1 and 2). The Diaozhai section (34°14.1′N, 109°10.2′E) is located on the second terrace at an elevation of 496 m asl and is 76 m above the river (Figs. 1 and 2). Artifacts were found within both loess and paleosol layers within exposures generated by brickworks excavations (Fig. 2).

At the Jijiawan section, the thickness of the exposed loess-paleosol sequence is 20.6 m. The lithostratigraphy of the upper part of the sequence (above 7 m) is easy to identify. Loess units are brown (7.5YR 4/4) and strong brown (7.5YR 4/6) in color, while the paleosols are yellowish red (5YR 4/6) and dark reddish brown (5YR 3/4). However, several of the loess units below 7 m are strongly weathered and it is difficult to distinguish loess and paleosol units in the field on the basis of either color or soil structure. Numerous Fe-Mn films are present in the lower part of the Jijiawan section; however, they are uncommon in the upper part of the sequence.

The exposed sedimentary sequence of the Ganyu section is about 35 m in thickness and contains six separate loess units with five intercalated paleosols, which are separated on the basis of pedogenic features such as texture and color. Loess units are light yellowish brown (10YR 6/4) in color and the paleosol layers are strong brown (7.5YR 5/6 and 7.5YR 4/6).

The thickness of the Diaozhai section from the top to the underlying gravel layer is 44 m. The sequence consists of two parts. The upper part above 27 m contains four separate paleosol units and four intercalated loess units. The color of the loess units is light yellowish brown (10YR 6/4) and very pale brown (10YR 7/4), while the paleosol layers are strong brown (7.5YR 4/6) and yellowish red (5YR 5/6). The lower part below 27 m consists of numerous thin layers (mainly less than 1 m) of floodplain sediments (sand, silt and clay) with horizontal bedding. The color of the layers is strong brown and reddish yellow (7.5YR 5/6 and 7.5YR 6/6). The base of the section, below 44 m, consists of a 5-m-thick gravel layer.

Methods

In order to provide a chronology for the three sites, OSL dating was used for the upper part of the loess-paleosol deposits, and magnetostratigraphy for the lower part. In addition, the loess-paleosol sequences were correlated to the typical Luochuan loess-paleosol sequence which has an orbitally-tuned time scale (Lu et al., 1999).

Sampling

Fieldwork at the Jijiawan, Ganyu and Diaozhai sections was carried out in November 2013 and May 2014. Samples from the three sections were collected from surfaces which were cleaned to a depth of at least 20 cm. A total of 10 OSL samples were taken by inserting metal tubes in the freshly cleaned sections. The samples were then wrapped in black plastic bags and sealed with waterproof tape.

At the Jijiawan section, sample JJW-1 was obtained from the lower part of the first loess layer (1.1 m depth). Samples JJW-2 and JJW-3 were obtained from the middle part of the first paleosol layer (2.2 m) and the second loess layer (3.2 m), respectively. At the Ganyu section, samples GY-1, GY-2 and GY-3 were obtained from the middle part of the first paleosol layer (1.5 m), the second loess layer (5.6 m) and the second paleosol layer (9.10 m), respectively. At the Diaozhai section, sample DZ-1 was obtained from the middle of the first paleosol layer (1.6 m), and samples DZ-2, DZ-3 and DZ-4 from the first loess unit at the depths of 3.1 m, 6.5 m and 9.2 m, respectively.

In addition, 73 oriented samples of dimensions 2 × 2 × 2 cm were collected at 15–30 cm intervals from the Jijiawan section for paleomagnetic measurements. In order to help resolve the pedostratigraphy, powder samples for magnetic susceptibility measurements were also taken from all three sections. At the Jijiawan section samples were taken at a 5-cm interval from the top of the first loess layer to the bottom of the sixth paleosol layer. At the Ganyu section, samples were taken at a 10-cm interval from the first paleosol layer, which is below the first loess unit, to the bottom of the section (24.2 m in total). At the Diaozhai section, samples were taken at a 5-cm interval from the top of the sequence (the modern cultivated soil and eolian sediments above the early Holocene paleosol S0) to the bottom (the top of the gravel layer). A total of 1607 samples were obtained for magnetic susceptibility measurements, which were made using a Bartington Instruments MS2 magnetic susceptibility meter after oven-drying at 37°C. The measurements were made at Nanjing University.

Optically stimulated luminescence (OSL) dating

The two light-exposed ends of each OSL samples were removed in the laboratory under subdued red light conditions. The unexposed sediments were prepared for equivalent dose (De) determination while the exposed sediments were retained for radioisotope and water content analyses. The pretreatment process consisted of removal of carbonates and organic material with 10% hydrochloric acid (HCl) and 30% hydrogen peroxide (H_2O_2), respectively.

Pure coarse-grained (63–90 μm) quartz (with no significant IRSL signal) was obtained after a 40 min hydrofluoric (40%) acid etch and 40 min 10% hydrochloric acid rinse. In order to obtain a K-rich feldspar extract, a portion of the 63–90 μm fraction was cleaned with 10% hydrofluoric acid for 15 min to remove coatings and the outer alpha irradiated layer and then rinsed in 10% hydrochloric acid for 20 min to remove any precipitated fluorides. K-rich feldspars were then floated off using an aqueous heavy liquid ($\rho = 2.58$ g cm^{-3}).

All luminescence measurements were performed using a Risø TL/OSL reader model DA-20 fitted with blue LEDs (470 nm, ~80 mW cm^2) and infrared (IR) LEDs (870 nm, ~135 mW cm^2)

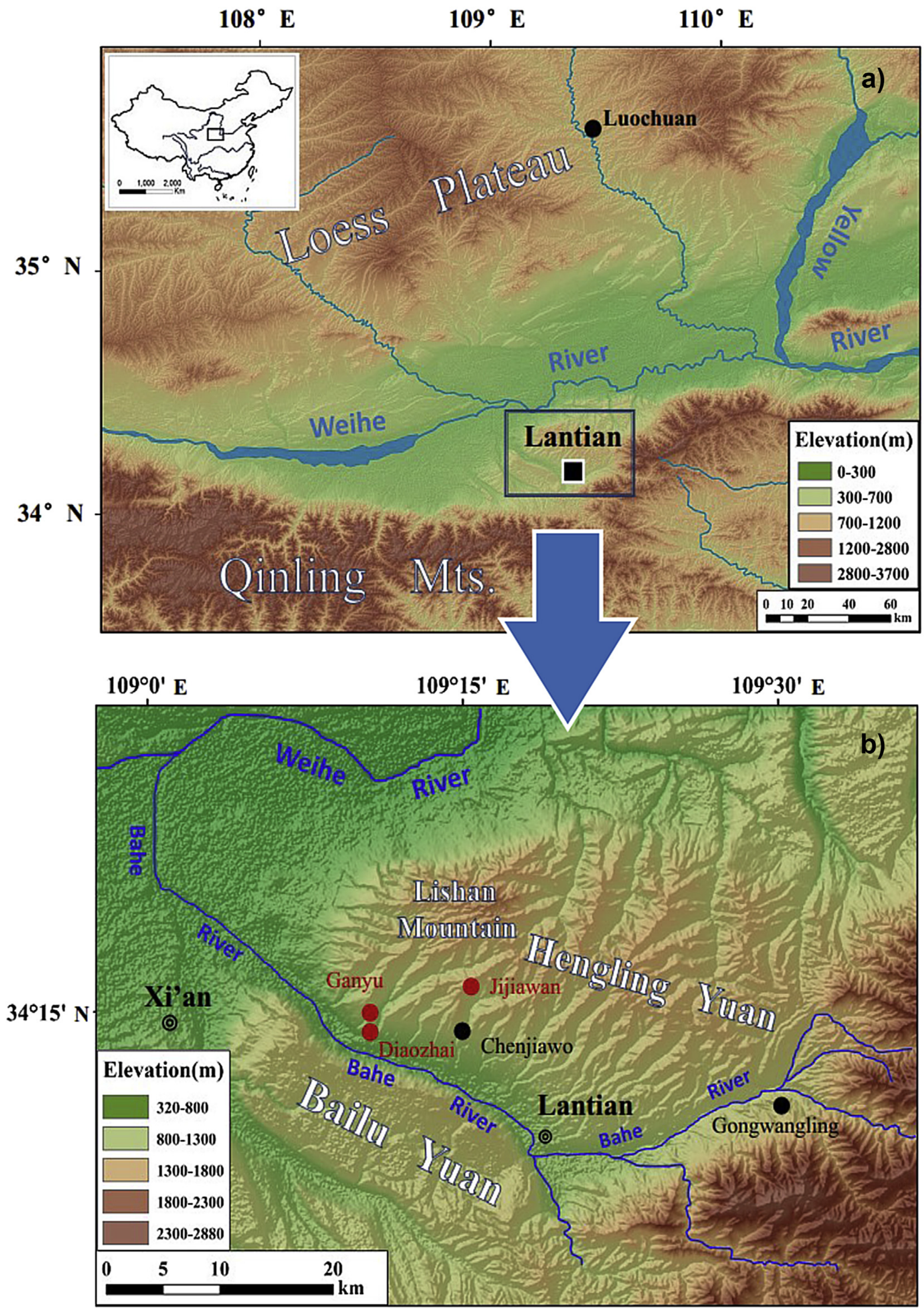

Figure 1. a) The Lantian area in central China; b) Archaeological sites (red dots) in the Lantian area studied in this paper. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

stimulated source in the Luminescence Dating Laboratory of Nanjing University. Quartz OSL signals were collected through 7.5 mm of Schott U-340 (UV) glass filter, and feldspar (post-IR) IRSL signals were detected through a Schott BG 39/Corning 7–59 filter combination. Quartz grains were mounted as large (8 mm diameter) aliquots on stainless steel discs and K-rich feldspars as small (2 mm) aliquots on stainless steel cups; silicone oil was used as an adhesive.

The quartz OSL dose measurements were carried out using a single-aliquot regenerative dose (SAR) (Murray and Wintle, 2003) protocol, which has been used successfully to date Chinese loess deposits elsewhere (Buylaert et al., 2007; Roberts, 2008; Lai, 2010;

https://doi.org/10.1016/j.yqres.2016.08.008 Published online by Cambridge University Press

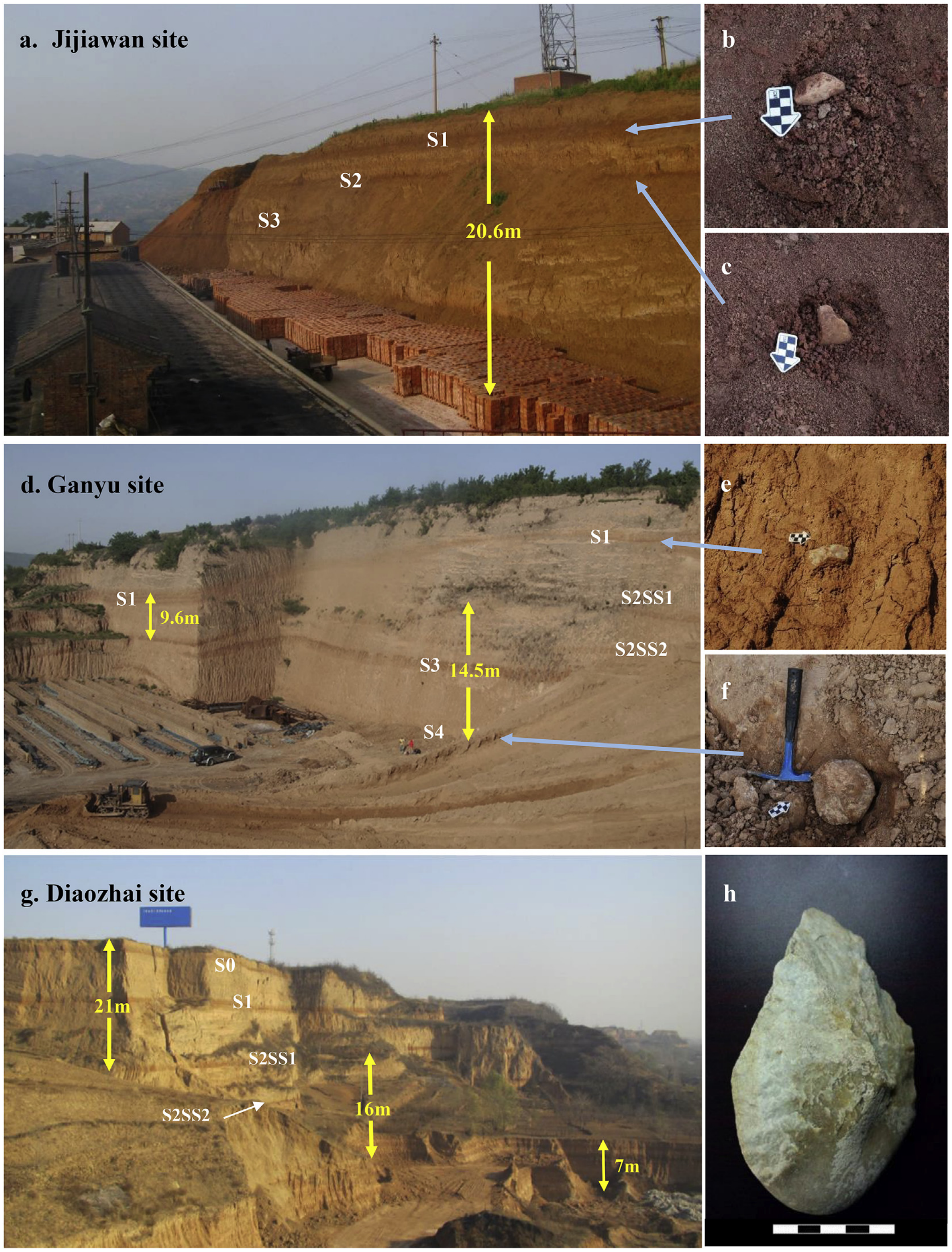

Figure 2. Loess-paleosol units and artifacts discovered *in situ* in the Jijiawan, Ganyu and Diaozhai sections (a. sedimentary sequence at the Jijiawan section; b, c. artifacts discovered *in situ* in the Jijiawan section; d. sedimentary sequence at the Ganyu section; e, f. artifacts discovered *in situ* in the Ganyu section; g. sedimentary sequence at the Diaozhai section; h. artifacts recovered from the Diaozhai section).

Lai and Fan, 2014; Yi et al., 2015, 2016). Early background (first 0.16 s minus background from 0.16 to 0.32 s interval) subtraction was used for signal integration (Cunningham and Wallinga, 2010) and dose response curves were fitted with a single-saturating exponential curve using Analyst version 4.31.7 (Duller, 2015). The dose recovery test (Murray and Wintle, 2003) was carried out and the ratios of the given doses to the measured doses using a 260°C preheat and 220°C cut heat preheat settings from the two samples (DZ-1 and DZ-2) were consistent with unity (Wintle and Murray, 2006) (DZ-1: 1.08 ± 0.01, $n = 9$; DZ-2: 1.06 ± 0.01, $n = 8$). For all samples, recuperation was <5% and the recycling ratio was between 0.9 and 1.1.

The coarse-grain (63–90 μm) K-feldspar dose was measured using an SAR-based post-IR IRSL protocol (pIRIR$_{290}$) (Thiel et al., 2011; Buylaert et al., 2012). Feldspar post-IR IRSL signals were derived from the integral of the first 2 s of 200 s of IR stimulation, minus a background based on the last 50 s. Sample doses were measured using a first IR stimulation temperature of 200°C (Yi

Table 1
Quartz OSL and pIRIR290 dating results for the Jijiawan, Ganyu and Diaozhai loess sections at Lantian (The absolute uncertainty of the water content estimates is ±5%. The pIRIR290 De values have a residual dose of 4.6 ± 0.6 Gy subtracted from the measured value. (n) denotes the number of aliquots contributing to the De).

Sample no.	Depth (m)	U/ppm	Th/ppm	K/%	Water content (%)	De (Gy)		Aliqouts Num (n)	Dose rate (Gy ka^{-1})		Age (ka)	
						Quartz De (Gy)	pIRIR290 De (Gy)		Quartz dose rate	pIRIR290 dose rate	Quartz age (ka)	pIRIR290 age (ka)
JJW-1	1.10	2.92 ± 0.11	14.3 ± 0.37	1.88 ± 0.06	15	162 ± 13	218 ± 10	4[a]/6[b]	3.36 ± 0.17	3.70 ± 0.17	48.3 ± 4.6	58.9 ± 3.8
JJW-2	2.20	2.45 ± 0.10	15.1 ± 0.39	1.84 ± 0.06	20	>179	358 ± 12	3/6	3.11 ± 0.15	3.46 ± 0.15	>57	103.7 ± 5.8
JJW-3	3.20	3.61 ± 0.12	14.0 ± 0.36	1.90 ± 0.06	15	>250	591 ± 21	3/9	3.43 ± 0.17	3.78 ± 0.17	>73	156.5 ± 9.2
GY-1	1.50	2.31 ± 0.09	12.8 ± 0.35	2.00 ± 0.06	20		319 ± 12	0/7		3.44 ± 0.15		92.8 ± 5.4
GY-2	5.60	2.73 ± 0.10	10.9 ± 0.31	1.78 ± 0.06	15		567 ± 41	0/10		3.27 ± 0.15		173.1 ± 14.8
GY-3	9.10	2.92 ± 0.11	13.5 ± 0.36	2.27 ± 0.07	20		>812	0/3		3.71 ± 0.17		>219
DZ-1	1.60	2.63 ± 0.10	13.0 ± 0.35	2.26 ± 0.06	20	13 ± 0.3	13 ± 1	11/5	3.39 ± 0.16	3.73 ± 0.16	3.8 ± 0.2	3.5 ± 0.3
DZ-2	3.10	2.39 ± 0.10	10.9 ± 0.31	1.86 ± 0.06	15	55 ± 4	74 ± 5	22/7	2.98 ± 0.15	3.32 ± 0.15	18.3 ± 1.7	22.2 ± 1.8
DZ-3	6.50	3.01 ± 0.11	12.1 ± 0.33	1.95 ± 0.06	15	156 ± 11	167 ± 5	7/6	3.20 ± 0.16	3.54 ± 0.17	48.6 ± 4.3	47.0 ± 2.6
DZ-4	9.20	2.90 ± 0.10	12.0 ± 0.34	1.88 ± 0.06	15	>200	239 ± 10	3/14	3.09 ± 0.16	3.43 ± 0.16	>65	69.8 ± 4.4

[a] Aliquot numbers using the quartz SAR protocol.
[b] Aliquot numbers using the pIRIR290 protocol.

et al., 2016) and are consistent with the findings of Li and Li (2012). As post-IR IRSL signals have been found to be hard to bleach (Buylaert et al., 2012; Yi et al., 2016), a residual dose of 4.60 ± 0.59 Gy was subtracted from all $pIRIR_{290}$ De values prior to age calculation based on the results of OSL bleaching experiments on loess deposits (Yi et al., 2016).

The dose rate was calculated from the concentrations of ^{238}U, ^{232}Th and ^{40}K, which were obtained by instrumental neutron activation analysis (INAA). Sample-specific water contents were determined by laboratory analysis, taking into account the measured variations in sediment water content and the mean water content of the loess, which are assumed to be 15 ± 5% and 20 ± 5% for the loess and the paleosol samples (Lu et al., 2007; Kang et al., 2013), respectively (Table 1). The elemental concentrations were converted into effective dose rates using the conversion factors of Guérin et al. (2011). Estimating the contribution of cosmic dosimetry is complex in the context of the study sections because of the variable thickness of the overburden. The cosmic ray dose rate was calculated following Prescott and Hutton (1994) and an uncertainty of 10% was assumed. For K-feldspar dose rates, a K concentration of 12.5 ± 0.5% and Rb concentration of 400 ± 100 ppm was assumed (Huntley and Baril, 1997). A small internal dose rate contribution from U and Th of 0.030 ± 0.015 Gy/ka and 0.06 ± 0.03 Gy/ka was included for quartz and K-feldspar, respectively (Mejdahl, 1987; Vandenberghe et al., 2008).

Paleomagnetic measurements

All samples were subjected to stepwise thermal demagnetization (THD) up to a maximum temperature of 690°C in field-free space (<300 nT), with a 50°C interval below 500°C and 20–35°C intervals above 500°C (17 steps). The demagnetized samples were measured using a 2G superconductor magnetometer in Nanjing University. Principal component directions were computed using a least-squares fitting technique (Kirschvink, 1980).

Results

All of the OSL dating results are listed in Table 1. At the Jijiawan section, the age of the uppermost sample (JJW-1) is approximately 59 ka and the ages of samples JJW-2 and JJW-3 are approximately 104 ka and 156 ka, respectively. At the Ganyu section, the OSL ages of samples GY-1 and GY-2 are about 93 ka and 173 ka, respectively, and GY-3 is older than 219 ka. At the Diaozhai section, the OSL age of the uppermost sample (DZ-1) is about 3.5 ka and the ages of samples DZ-2, DZ-3 and DZ-4 are about 22 ka, 47 ka and 70 ka, respectively.

The magnetic susceptibility (MS) values of the Jijiawan section range from 19–317 × 10^{-8} m^3/kg (Fig. 3). The MS varies significantly above 7.6 m (the peak value of 317 × 10^{-8} m^3/kg occurs within the third paleosol), whereas the values are relatively constant below, except for an abrupt shift at 13.0 m. The MS values of the Ganyu section range from 34–366 × 10^{-8} m^3/kg. The record exhibits a consistent pattern of high values in the paleosols and low values in loess layers. The peak values in the third and fourth paleosol units are 344 and 366 × 10^{-8} m^3/kg, respectively. The MS values of the Diaozhai section range from 5.3–277 × 10^{-8} m^3/kg. The MS exhibits a pattern typical of loess-paleosol sequences above 27.0 m, with higher values in the paleosol layers and lower values in the loess layers. The MS below 27.0 m varies significantly, with a peak at 30.0 m. However, the values below 30.0 m are relatively constant.

The thermal demagnetization results for the Jijiawan section are illustrated in Figure 4. A secondary viscous magnetization was removed between 200 and 300°C and the characteristic remanent magnetization (ChRM) was typically isolated between 300 and 580°C. This demagnetization behavior indicates that magnetite and/or maghemite are the principal ChRM carriers. All of the samples exhibit univectorial decay of the magnetization towards the origin and all are normally magnetized (Fig. 3).

Most of the *in situ* lithic artifacts collected from the Jijiawan and Ganyu sections are small in size (Fig. 5). At Jijiawan, eight artifacts were found in the first paleosol layer (2 m), four artifacts in the second paleosol layer (4.2 m), one artifact in the third layer (6.6 m) and two artifacts in the fourth paleosol layer (at depths of 7.60 m and 9.65 m, respectively). A total of 21 artifacts were collected, including 4 cores, 9 flakes and 8 chunks/chips. Three of the cores are hard-hammer cores and one of them is a bi-polar core. At the Ganyu site, one core was found in the first paleosol layer (2.7 m) and 27 artifacts were found in the fourth paleosol layer (20 m). A total of 31 artifacts were found, with a similar flaking technology to that at Jijiawan, including 6 cores, 4 flakes, 3 broken flakes, 17 chunks/chips and 1 retouched tool (scraper). In the Diaozhai section, a retouched tool (Fig. 2h) was found on the surface in the course of sample collection in 2013. In addition, hundreds of stone artifacts were collected from the Diaozhai section in 2009, including 22 retouched tools and nearly 100 cores and flakes, with two of the flakes found *in situ* in the first loess unit (Wang et al., 2014a). The raw materials of all these artifacts are vein quartz and quartz sandstone and direct hard hammer percussion was the principal stone-knapping technique. Although the stone artifacts found in these sections are of varying ages, they exhibit little technological variation.

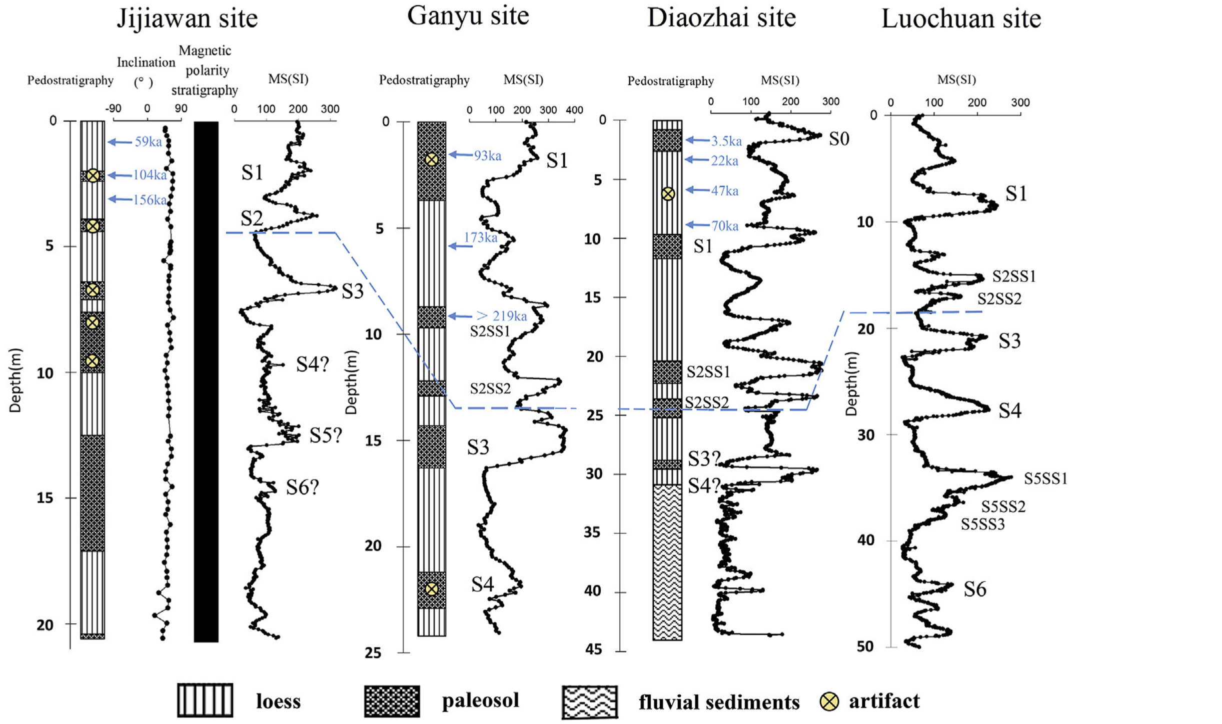

Figure 3. Magnetostratigraphy, pedostratigraphy, and magnetic susceptibility stratigraphy of the loess-paleosol sequence at the Jijiawan, Ganyu, Diaozhai and Luochuan sections.

Discussion

Pedostratigraphy of the Jijiawan, Ganyu and Diaozhai sections

At the Jijiawan section, the OSL age of the uppermost sample (JJW-1) is dated to approximately 59 ka, confirming that the first loess unit was deposited within the last glacial period (L1). The ages of samples JJW-2 and JJW-3 demonstrate that the first paleosol unit was formed in the last interglacial period (S1). According to the typical interpretation of the loess-paleosol sequence of the Chinese Loess Plateau (CLP), the loess-paleosol units beneath S1 date from the penultimate glaciation and earlier. All of the paleomagnetic samples from the Jijiawan section are normally magnetized and therefore the studied loess-paleosol sequences are correlated with the Brunhes normal magnetic chron (N1). This result demonstrates that the exposed loess deposits in the Jijiawan section are younger than the Brunhes/Matuyama boundary (0.78 Ma). As discussed in previous publications, the Brunhes/Matuyama boundary in Chinese loess-paleosol sequence is located in the upper part of paleosol S8 (Liu et al., 2015). Therefore, the oldest loess unit in the Jijiawan section is younger than S8.

In order to obtain more precise age control, the MS and soil stratigraphy of the Jijiawan section were compared with that at the classical Luochuan site in the central CLP (Lu et al., 1999). Several points are noteworthy. Firstly, the thickness of the first three paleosol units at Jijiawan (above 7.6 m) is much less than that at Luochuan; this may be caused by the nature of the local topography and/or by the distance to the dust source. Because the Jijiawan site is located in an area of high relief, it is possible either that the surface has received less dust deposition or that some of the loess has been eroded. Secondly, the MS record below 7.6 m depth at Jijiawan is significantly different to that at Luochuan in that the

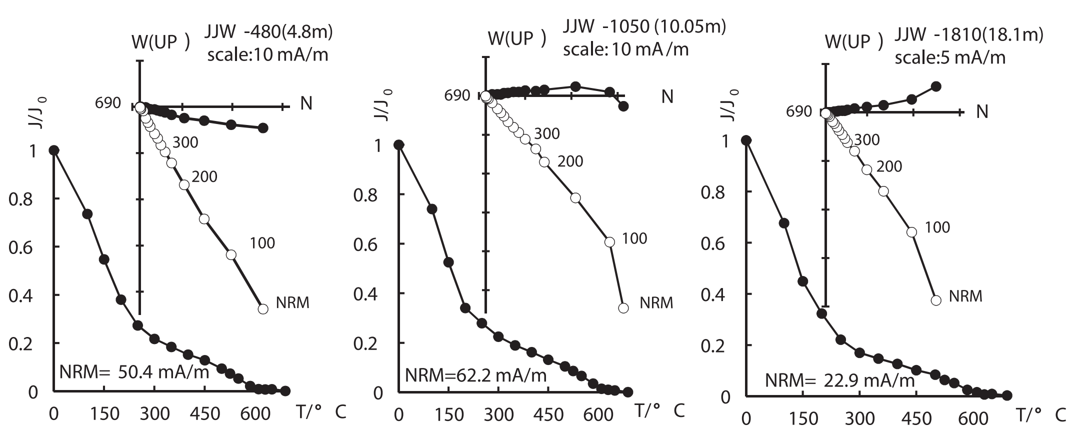

Figure 4. Representative vector end-point plots for progressive thermal demagnetization of selected samples from the Jijiawan section. Open (closed) circles indicate projections onto the vertical (horizontal) plane.

https://doi.org/10.1016/j.yqres.2016.08.008 Published online by Cambridge University Press

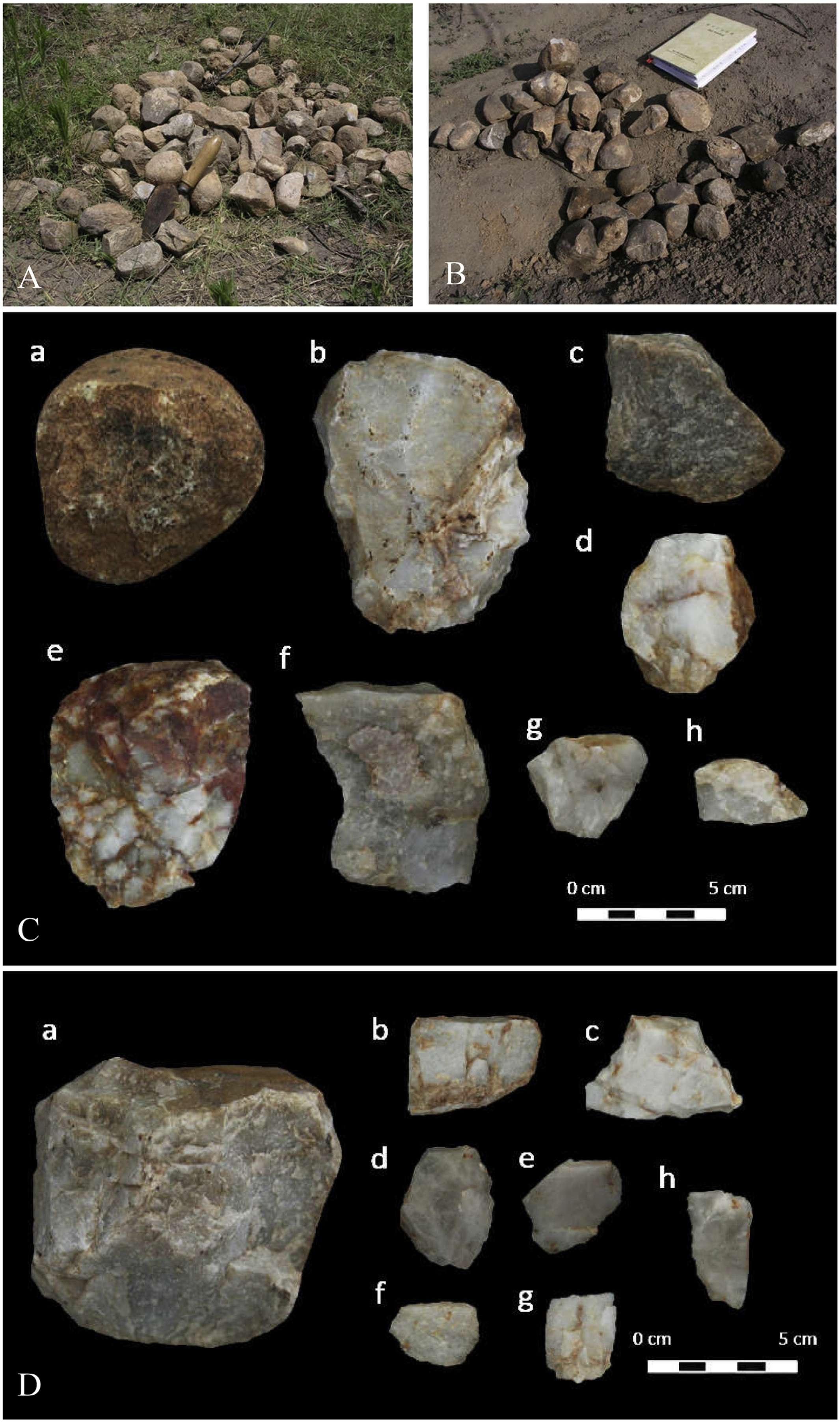

Figure 5. A) Artifacts collected from the brickworks at the Diaozhai section; B) artifacts collected from the brickworks at the Ganyu section; C) lithic artifacts collected from the Jijiawan section (a–d: cores; e–h: flakes); D) lithic artifacts collected from the Ganyu section (a–b: cores; c–g: flakes; h: scraper).

values in the former record are relatively constant. The reason for this may be that soil magnetic properties vary significantly depending on local conditions of temperature and moisture. In particular, ferromagnetic minerals are destroyed under water-logged pedogenic conditions (Zhao et al., 2008). Therefore, the abrupt shift of the MS to lower values below 7.6 m depth at Jijiawan may indicate that this part of the sequence was formed under a moist climate. This possibility is supported by the frequent occurrence of Fe–Mn films within the lower part of the section. In contrast, the upper part of the sequence may have been deposited in a cooler and drier environment. Nevertheless, there is still an overall strong correlation between the Jijiawan MS record and that of loess-paleosol sequences in the central CLP (Fig. 3). Based on these observations, we assign the first, second, and third paleosol units at Jijiawan to S1, S2, and S3, respectively, as in the central CLP (Liu, 1985; Lu et al., 1999). In addition, we suggest that S4, S5 and S6 are located at the depth intervals of 9.6–10.1 m, 11.9–12.8 m and 14.4–14.8 m, respectively.

At the Ganyu section, the OSL dating results of samples GY-1 and GY-2 indicate that the first paleosol corresponds to paleosol S1 in the central CLP and the second loess layer corresponds to the Penultimate Glaciation loess (L2). The age of sample GY-3 is older than 219 ka, indicating that the second paleosol corresponds to S2, or is possibly older than S2. In order to confirm the ages of successive paleosol layers, we then compared the strata thickness with the equivalent thicknesses on the CLP. The thicknesses of the second loess unit and that of the second to the third paleosol units are about 5 m respectively. This is almost the same as the thickness of L2 and the thickness from S2SS1 to S2SS2 at the Luochuan site in the central CLP. Furthermore, by comparing the MS record of the Ganyu section with that at Luochuan, we assign the second loess unit to L2 and the two paleosol layers from 8.4 to 13.6 m to S2SS1 and S2SS2, respectively. We conclude that the fourth paleosol layer is S3, for the following two reasons: (1) the similarity of the thickness of S3 at Luochuan; and (2) the MS record for the Ganyu section contains two peaks in this paleosol layer, which is the same as that recorded at Luochuan (S3). Using a similar approach, we conclude that the fifth paleosol unit is S4.

When reviewing the MS records of the Jijiawan and Ganyu sections, we found that the highest MS values of S2 and S3 ($\geq 300 \times 10^{-8}$ m^3/kg) are greater than those at Luochuan ($\leq 250 \times 10^{-8}$ m^3/kg). In addition, the highest MS values of the same layers in the Duanjiapo section (Zheng et al., 1992), located on the south bank of the Bahe River, is approximately the same as at the Jijiawan and Ganyu sections. It is possible that this phenomenon was caused by the nature of local climatic and weathering conditions, and that the environment was warmer and moister than in the central CLP during the interval when S2 and S3 formed.

At the Diaozhai section, the uppermost OSL date (sample DZ-1) confirms that the first paleosol unit was deposited during the Holocene (S0). The other OSL ages (samples DZ-2, DZ-3 and DZ-4) demonstrate that the first loess unit is the Malan loess (L1, the last glacial loess). From a comparison of the MS records it can be concluded that the first, second, third and fourth paleosol units in the Diaozhai section are S0, S1, S2SS1 and S2SS2, respectively.

Ages of the lithic artifacts and hominin behavior at Lantian

On the basis of the chronology described above, the buried lithic artifacts in the Jijiawan section are located in S1 (correlative with MIS 5), S2 (correlative with MIS 7), S3 (correlative with MIS 9) and possibly S4 (correlative with MIS 11). These paleosol units in the central CLP were dated to 71–129 ka, 188–254 ka, 279–334 ka and 385–428 ka, respectively, based on tuning of the MS record to the summer insolation record for the latitude of 65°N (Lu et al., 1999). This chronology enables the age of the artifacts to be estimated. These paleosol units, within which all of the artifacts in the Jijiawan section were found, were formed in a relatively warm and humid climate.

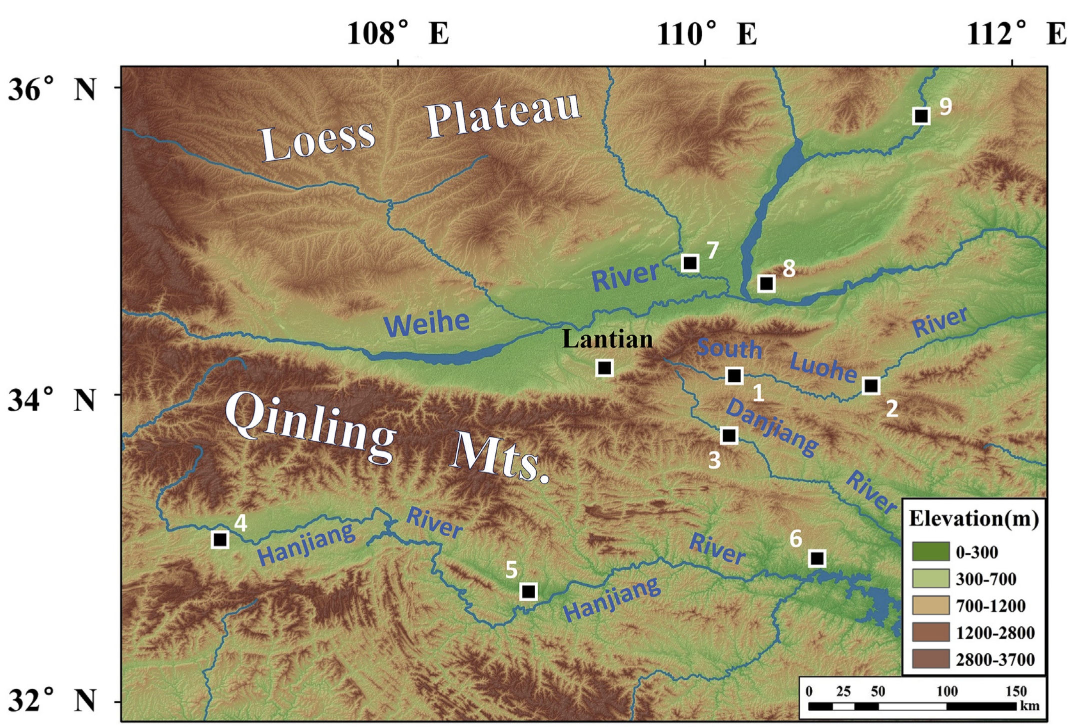

Figure 6. Location of the Lantian and other coeval Pleistocene archaeological sites around the Qinling Mountains. 1. Luonan Basin; 2. Lushi Basin; 3. Shangdan Basin; 4. Hanzhong Basin; 5. Ankang Basin; 6. Yunxian Basin; 7. Dali; 8. Xihoudu; 9. Dingcun.

In the Ganyu section, we found one core buried at the bottom of S1 and other stone tools (flakes and chunks) in the middle of S4 (correlative with MIS 11). The age of these artifacts spans the intervals of 71–129 ka and 385–428 ka, respectively. The results for the Jijiawan and Ganyu sections suggest that during the middle to late Pleistocene the hominins living in the southern CLP areas were adapted to a warm and humid climate.

In the Diaozhai section, two flakes were found *in situ* within L1 (correlative with MIS 2–4) (Wang et al., 2014a) and thus the ages of these artifacts are younger than 71 ka. The fact that these artifacts are dated to the last glacial period demonstrates that the early hominins were able to survive in the relatively harsh environment of the Lantian area at that time.

Characteristics of the lithic artifacts and hominin behavior in the vicinity of the Lantian area

In the vicinity of the Lantian area, hundreds of Paleolithic sites and tens of thousands of artifacts have been discovered in the Luonan Basin (Wang, 2005; Lu et al., 2007, 2011b, 2012), Lushi Basin (Wang et al., 2008; Lu et al., 2011a), Shangdan Basin (Wang et al., 2013), Hanzhong Basin (Sun et al., 2012; Wang et al., 2014b), Ankang Basin (Wang and Lu, 2014) and Yunxian Basin (Feng et al., 2011; Sun et al., 2016) (Fig. 6). The lithic technologies in these areas have many similarities: 1) most of the tools were made from locally-derived alluvial pebbles consisting of greywacke, quartz, sandstone and igneous rocks; 2) the main percussion techniques used were direct hard hammer percussion and bi-polar techniques; 3) the lithic artifacts comprise hammer stones, cores, flakes, retouched tools and flaking debris; 4) several examples of Acheulian technology Mode II (large cutting tools such as hand-axes, picks and cleavers) have been identified but are undated. Therefore, we speculate that there were technological linkages between the sites in these areas.

In addition, we conducted a survey of the Palaeolithic chronology of other sites in the vicinity of the Eastern Qinling Mountains (Table 2), including Dali Man (Chen et al., 1984; Xiao et al., 2002; Yin et al., 2011), Xihoudu (Wei, 2000) and Dingcun (Liu et al., 1995; Wu and Liu, 2002) (Fig. 6). The ages of the majority of the artifacts or fossils are middle or late Pleistocene. In the eastern Qinling Mountains, the most easterly Paleolithic site is Qiaojiayao (Lu et al., 2011a), which is located in the Lushi Basin, approximately 170 km from Lantian. To the south, Hanzhong Basin is about 250 km from Lantian; and to north the Dingcun sites are about 270 km from Lantian. These Pleistocene archaeological sites cover a total area of more than 40,000 km^2. Furthermore, the elevation difference (at least 385 m) between the Jijiawan and Ganyu indicates that the elevation ranges of the areas inhabited by hominins were almost 400 m during the middle Pleistocene. Moreover, the spatial distribution of these Pleistocene archaeological sites suggests that a large area around the Eastern Qinling Mountains was occupied by hominins during the middle to late Pleistocene.

Table 2
Chronology of Paleolithic sites near the Qinling Mountains.

Study	Sections	Age	References
Luonan Basin	Shangbaichuan site	From ~800 ka	Lu et al. (2007, 2011b)
	Longyadong Cave	390–274 ka	Wang (2005)
			Sun et al. (2013)
	Liuwan site	From ~600 ka	Lu et al. (2007)
Lushi Basin	Qiaojiayao site	620–600 ka	Lu et al. (2011a)
Hanzhong Basin	Yaochangwan site	From ~600 ka	Sun et al. (2012)
	Hejialiang site	~86 ka	Sun et al. (2012)
Yunxian Basin	Xuetangliangzi site	~936 ka	Feng et al. (2011)
	Houfang and Dishuiyan sites	150–50 ka	Sun et al. (2016)
Dali	Dali Man site	~270 ka	Xiao et al. (2002)
			Yin et al. (2011)
Xihoudu	Xihoudu site	1.27 Ma	Zhu et al. (2003)
Dingcun	Dingcun site	>130 ka	Wu and Liu (2002)
		>247 ka	Liu et al. (1995)
		~124 ka	Chen et al. (1984)
		160–210 ka	

Conclusions

In recent years, nearly 1000 lithic artifacts have been discovered in the Lantian area of China. Based on a combination of OSL and paleomagnetic dating and stratigraphic correlation we have provided new age constraints for hominin occupations in this region. The ages of the artifact layers in the Jijiawan section are dated to 71–129 ka, 188–254 ka, 279–334 ka and 385–428 ka; those at the Ganyu site are dated to 71–129 ka and 385–428 ka; and the artifacts at the Diaozhai site are dated from 71 ka until the late Pleistocene. The technological features of the stone tools found in these sites exhibit relatively little variation, indicating a long-established, stable technology and long-term hominin occupation of the Lantian area.

Our results also suggest that the early hominins were more adapted to a warm and humid climate during the middle to late Pleistocene; however, they were also able to adapt to the relatively harsh environment of the late Pleistocene. Furthermore, from a synthesis of previous studies, we conclude that there were technological linkages between the various areas of occupation; and that the hominins had a large altitudinal and spatial range (more than 400 m and more than 40,000 km^2, respectively) in the vicinity of the Qinling Mountains during the middle to late Pleistocene.

Acknowledgments

This research was supported by the Global Change Program of the Ministry of Science and Technology of China (Grant No. 2016YFA0600503), the National Natural Science Foundation of China (Grant Nos. 41472138 and 41472026) and the Graduate Student Research Innovation Program of Jiangsu Province (Grant No. KYZZ_0033). We are grateful to Dr. Jan Blomendal for significantly correcting English of this paper.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.yqres.2016.08.008.

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