Journal of Human Evolution 108 (2017) 1–10

Contents lists available at ScienceDirect

Journal of Human Evolution

journal homepage: www.elsevier.com/locate/jhevol

Consistent C_3 plant habitat of hominins during 400–300 ka at the Longyadong Cave site (Luonan Basin, central China) revealed by stable carbon isotope analyses of loess deposits

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A R T I C L E I N F O

Article history:
Received 29 August 2015
Accepted 20 January 2017
Available online 28 April 2017

Keywords:
Middle Pleistocene
Hominin behavior
Vegetation
Paleolithic
C_3 and C_4 plants
East Qinling Region

A B S T R A C T

The proportions of woody and grassland taxa in terrestrial ecosystems played an important role in the origin and evolution of early Palaeolithic hominins. However the influence of ecosystem changes on hominin behavior and adaptations in Asia has not been studied in detail. Hominins have exploited the Luonan Basin in the Eastern Qinling Mountains, central China, since the early Paleolithic. Dated sites, consisting of alternating loess and soil deposits with in situ artefacts, are common in the region, and provide a detailed record of Early to Middle Pleistocene hominin environments. Here, we present the results of measurements of the stable carbon isotopic composition of soil organic matter ($\delta^{13}C_{SOM}$) in the loess-paleosol sequences from the Longyadong Cave site. Our analyses of $\delta^{13}C_{SOM}$ show that for at least 400 ka the Longyadong Cave site and its surroundings were dominated by C_3 woody plants, whereas the nearby Liuwan site was dominated by C_4 and C_3 mixed grassland or woody grassland vegetation. These findings demonstrate that between 400 and 300 ka in the Luonan Basin, hominins occupied a habitat consisting of a mosaic of grassland and woodland/forest. Although the vegetation of the region changed in response to the glacial–interglacial climatic cycles, patches of woody vegetation in landscapes such as at Longyadong Cave site persisted continuously. Such environments seem to be have been favored by hominins living in the Luonan Basin, possibly because they provided a diverse range of food resources during both glacial and interglacial intervals of the Middle Pleistocene, when most of northern China was experiencing an increasing trend of drying and cooling and steppe environments were expanding. Thus, the Luonan Basin would have served as a refugium for hominin occupation in China during the Middle Pleistocene.

1. Introduction

Environmental change, particularly on land, is considered to have played a critical role in the origin, evolutionary events and adaptation of hominins (Dart, 1925; Vrba, 1984, 1996; Elton, 2001, 2008; van der Merwe et al., 2003; deMenocal, 2004, 2011; Dennell and Roebroeks, 2005; Cerling et al., 2011; Reynolds et al., 2015). In Africa, evidence from $\delta^{13}C$ data, fossil bovids, and plant-wax biomarkers indicate that hominins evolved alongside the contracting forest cover and the concomitant spread of C_4 grasses during the Pliocene and Pleistocene (Cerling, 1992; Bobe and Eck, 2001; van der Merwe et al., 2003; Bobe and Behrensmeyer, 2004; Feakins et al., 2005; Cerling et al., 2011). However, the European and Asian environments into which hominins moved from Africa during the ongoing dramatic environmental and biome changes are not well understood. This is due primarily to the paucity of in situ archeological evidence and systematic multi-disciplinary research (as mentioned in Norton and Braun, 2010; Dennell, 2010). Comprehensive understanding of the links between environmental change and hominin adaptations can be gained only from research into the composition of the vegetation and climatic changes at archaeological sites both with in and outside Africa.

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http://dx.doi.org/10.1016/j.jhevol.2017.01.011

In Europe and Asia, the nature of hominin habitat preference and adaptation in the Early to Middle Pleistocene is still actively discussed (e.g., Potts, 1998; Elton, 2008; Dennell, 2009, 2013; Pei et al., 2009; Shen et al., 2009; Ao et al., 2010; Belmaker, 2010; Dennell et al., 2011; Louys and Turner, 2012; Wurster and Bird, 2014; Potts and Faith, 2015). Gaining a fuller understanding of these issues requires a synthesis of reliable environmental and paleoanthropological data from various geographic landscapes and on different time scales. Northern and central China have long records of human occupation, and thus provide the opportunity to undertake such syntheses. In northern China, the oldest lithic assemblages are dated to 1.66 Ma at Majuangou III, in the Nihewan Basin (Fig. 1) (Zhu et al., 2003, 2004). In addition, the earliest fossil hominin evidence is the cranium from Gongwangling (Fig. 1), Lantian, ~70 km west of the Luonan Basin, for which there was a commonly cited age estimate of 1.15 Ma (An and Ho, 1989), but which was recently revised to ~1.63 Ma by Zhu et al. (2015). Other Paleolithic sites of Early Pleistocene age have been discovered at Xiantai (1.36 Ma; Deng et al., 2006), Xiaochangliang (1.36 Ma; Zhu et al., 2001), Feiliang (1.2 Ma; Deng et al., 2007), Donggutuo (1.1 Ma; Wang et al., 2005) in the Nihewan Basin (Fig. 1), and Xihoudu (1.27 Ma; Zhu et al., 2003) (Fig. 1) in Shanxi Province. These sites represent the earliest colonization of *Homo erectus* of northern China. It is still debated whether or not the early hominins could have lived continuously in the high latitudes of northern China and Europe and were adapted to the relatively colder glacial periods during the Early Pleistocene (Dennell, 2009; Pei et al., 2009; Ao et al., 2010; Dennell et al., 2011, 2013; Louys and Turner, 2012).

In the Middle Pleistocene, consistent with the long-term global cooling trend (Lisiecki and Raymo, 2005), the climate in northern China changed from relatively warm and humid to cold and dry (Ding et al., 2002; Lu et al., 2010). Typical hominin occupation sites in this time period are from the Zhoukoudian Locality 1 (Fig. 1). Hominin-fossil-bearing layers in the Zhoukoudian Locality 1 had the long-accepted age range of 500 to 230 ka (Wu et al., 1985; Yuan et al., 1991; Grün et al., 1997), but this was revised to ~780–400 ka by Shen et al. (2009). Evidence of hominin settlement in the Middle Pleistocene is also reported from the Nihewan Basin, with ages of ~0.5 Ma at Xujiayao (Wang et al., 2008c), ~0.4 Ma at Hougou (Zuo et al., 2011), ~0.3 Ma at Dongpo (Liu et al., 2010); and at Chenjiawo in Lantian, which is dated to ~0.65 Ma (An and Ho, 1989). The ages of most of these Middle Pleistocene lithic sites are estimated based on extrapolation of sedimentation rates and there is considerable uncertainty regarding their reliability.

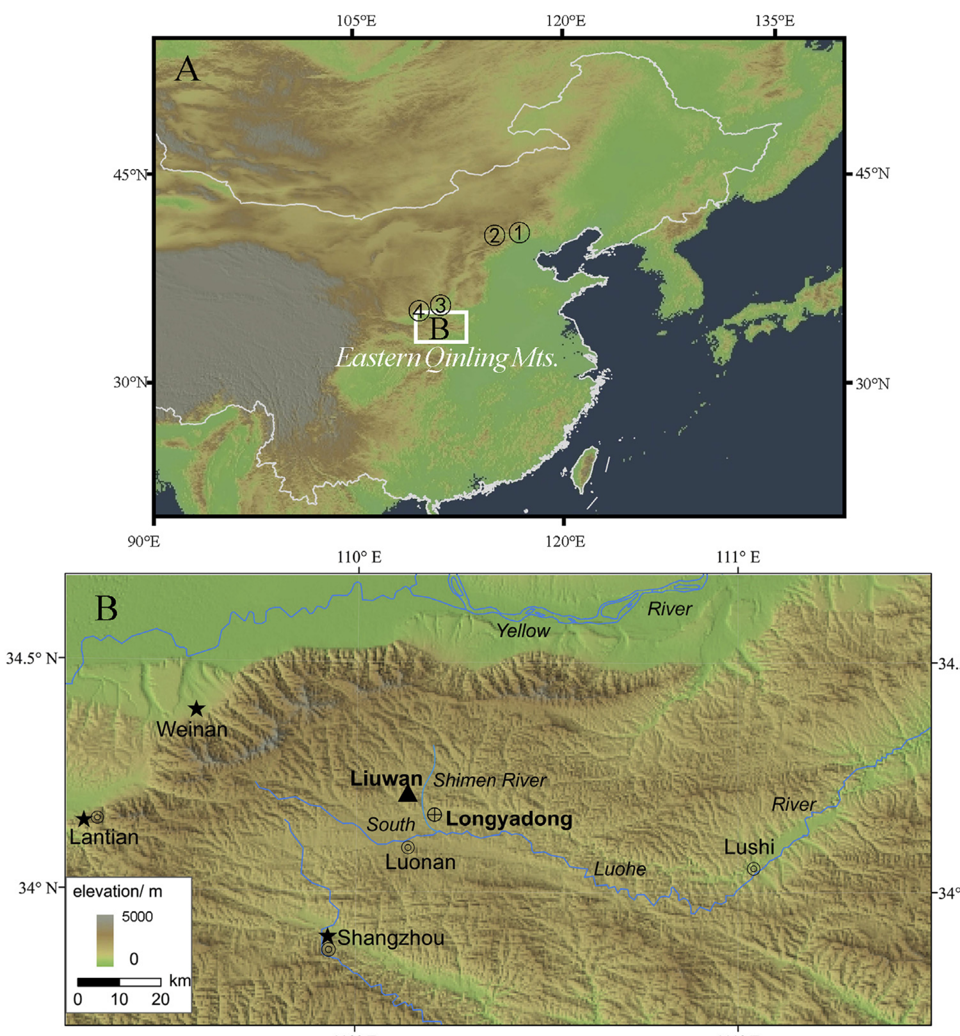

Figure 1. A: Study area and the main Palaeolithic sites referenced in the text. 1 Zhoukoudian; 2 Nihewan; 3 Xihoudu; 4 Lantian. B: Geographic setting of the Luonan Basin and the location of the Liuwan loess-Palaeolithic site (represented by a black triangle) and Longyadong Cave (represented by a circle and cross). Other sites in the vicinity with paleoenvironmental data are indicated by black stars.

During the past three decades, abundant Paleolithic artefacts have been collected from open-air sites and loess deposits in the upper South Luohe River (Fig. 1), Luonan Basin, central China (Wang et al., 1997, 2008b, 2011; Wang and Huang, 2001; Wang, 2005; Lu et al., 2007, 2011a, 2011b, 2012; Shaanxi Provincial Institute of Archaeology et al., 2007; Shaanxi Provincial Institute of Archaeology and Museum of Luonan County, 2008; Sun et al., 2013, 2014) and the adjacent region at Lantian (Wang et al., 2014; Zhuo et al., 2016). The abundant stone tools indicate that the Luonan Basin was an important area for hominin occupation during the Pleistocene. Since 2010, tens of thousands of in situ artefacts have been excavated from the loess deposits in Luonan Basin (Wang et al., 2011; Lu et al., 2011a, b, 2012) and the Lantian region (Wang et al., 2014; Zhuo et al., 2016), and the sites provide an excellent opportunity to study hominin behavior and environmental change, principally vegetation turnover, landform processes and climatic change. In addition, the loess deposits in northern China have been extensively studied to reconstruct changes in the Quaternary environment, and have been shown to be one of the most valuable terrestrial paleoenvironmental archives (e.g., Liu, 1985; Lu et al., 2007, 2010, 2012). Eolian loess is widely distributed on various topographies and at various altitudes in the Luonan Basin, with thicknesses ranging from several meters to several tens of meters (Lu et al., 2007, 2012; Zhang et al., 2012). Detailed dating of the loess-paleosol sequences demonstrates that loess accumulation began at least 1.1 million years ago (Lu et al., 2007, 2012). The presence of in situ cores, flakes and retouched stone tools in these deposits shows that hominins intensively colonized the region during 800–600, 400–300 and 200–100 ka (Lu et al., 2007, 2011a; Sun et al., 2013). Linking these archaeological data with the pattern of loess deposition presents an excellent opportunity to study the hominin occupation of the Luonan Basin in the context of paleoenvironmental change.

The most intensively studied archaeological site in the Luonan Basin is Longyadong Cave. The cave and its vicinity have been investigated several times since 1977 (Wang, 2005; Shaanxi Provincial Institute of Archaeology and Museum of Luonan County, 2008). One molar of *H. erectus* and tens of thousands of stone artefacts and mammalian fossils have been collected from an area of 20 m^2 in the cave (Xue, 1987; Xue et al., 1999; Wang and Huang, 2001; Wang, 2005; Shaanxi Provincial Institute of Archaeology and Museum of Luonan County, 2008). Independent dating results indicate that hominins occupied the cave continuously between 389 ka and 274 ka (Wang and Huang, 2001; Sun et al., 2013). In the present study, we sampled the sedimentary sequence at the entrance to Longyadong Cave (Fig. 1) and analyzed the stable carbon isotopic composition of soil organic matter ($\delta^{13}C_{SOM}$) in order to reconstruct the vegetation during the period of hominin occupation. In addition, an in situ loess-Paleolithic site, close to Longyadong Cave (Fig. 1), was sampled and analyzed for comparison with Longyadong Cave. The work constitutes the first analysis of the context of the vegetation at the time of hominin occupation near the watershed of the South Luohe River. This study provides new evidence of vegetation variation in hominin habitats in central China during the Middle Pleistocene, supporting the idea that the geographic boundary between south and north China probably acted as a refugia for hominin adaptation and distribution in Pleistocene Asia (Dennell, 2009; MacDonald et al., 2012; Louys and Turner, 2012).

2. Materials and methods

2.1. Geographical setting

The Luonan Basin is one of several inter-montane basins in the Eastern Qinling Mountains, central China (Fig. 1). It is 70–80 km long and 20–30 km wide. The South Luohe River is a major river that cuts through the Luonan Basin, originating from the Huashan Mountains to the west of the basin and flowing out of the basin to the east. Landforms along the course of the river include mountains, hills, basins, gorges and river terraces. The higher terraces and the tops of the mountains around the basin are composed of metamorphic or calcareous bedrock covered by a mosaic of loess deposits up to 2–3 m thick. Within the valleys, however, tens of meters of loess deposits cover the lower terraces and the bottom of the basin and exhibit distinct loess-paleosol alternations.

The Luonan Basin is located in the transition zone between the warm temperate and subtropical zones in central China. The annual mean temperature is 11 °C, and the basin bottom setting is humid to sub-humid with a mean annual rainfall of ~706 mm. Precipitation in the Luonan Basin is mainly controlled by the Asian Monsoon circulation. The majority of the modern vegetation consists of secondary communities. Shrubland, grassland and cultivated land dominate the lower terraces and the bottom of the basin, with temperate mixed forest on the mountain slopes and higher terraces.

2.2. The Longyadong T1 section

Longyadong Cave (34° 07′ 39″ N, 110° 09′ 51″ E) is located on the second river terrace and is on the left bank of the Shimen River (Fig. 2). It is one of the first-order branches of the South Luohe River, and is about 3 km north of Luonan County town (Fig. 1). The cave is one of the vertical karstic fissure caves of the Huashilang locality. The cave has a southern aspect, is about 6–8 m long and 1.5–2.5 m wide and would have provided a living space of up to 20 m^2 (Wang, 2005; Shaanxi Provincial Institute of Archaeology and Museum of Luonan County, 2008).

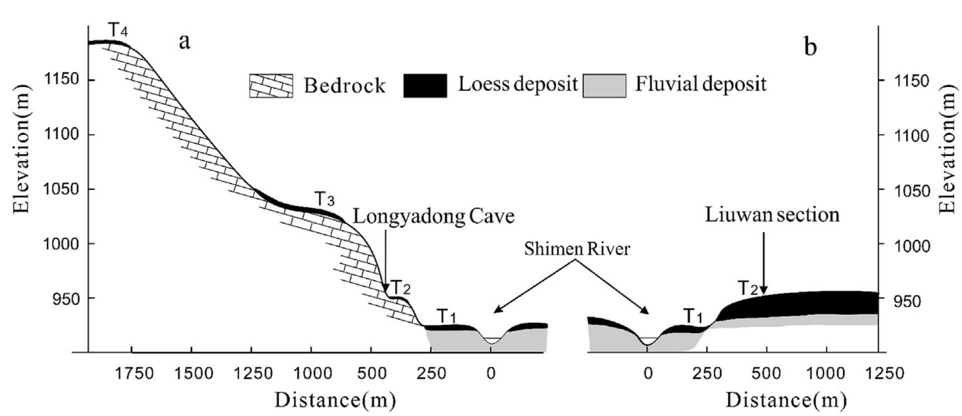

Figure 2. Geomorphological context of (a) Longyadong Cave and (b) the Liuwan loess-Palaeolithic site. T = Trenches, see text for further details.

Table 1
Fossil mammals discovered in the inner Longyadong Cave (LYD section in Fig. 3b) and their biogeographic distribution (modified from Xue et al., 1999).[a]

Taxa		Biogeographic region	Taxa		Biogeographic region
Soricidae	? *Soriculus* sp.	O	Mastodontoidae	Mastodontoidae gen. et sp. indet.	O, P
Talpaidae	*Talpa* sp.	P, O	Elephantidae	*Stegodon* sp.	O, P
Chiroptera	Chiroptera fam. gen. et sp. indet.	P, O	Canidea	*Nyctereutes* cf. *N. sinensis*	P
Hominidae	*Homo erectus*	P, O		Canidea gen. et sp. indet.	O, P
Ochotonidae	*Ochotona* sp.	P	Procyonidae	*Ailuropoda melanoleuca faveolis*	O
Sciuridae	*Sciurotamias* cf. *S. teilhardi*	O	Ursidae	*Ursus* cf. *U. etruscus*	P
	Tamiops swinhoei	O, P	Mustelidae	*Martes* sp.	P, O
	Callosciurus cf. *C. erythraeus*	O	Hyaenidae	*Hyaena sinensis* (*Pachycrocuta brevirostris*)	P, O
Petauristidae	*Belomys parapearsoni*	O	Equidae	*Equus* cf. *E. sanmeniensis*	P
	Aeretes sp.	O	Tapiridae	*Tapirus sinensis*	O
Cricetidae	*Eospalax* sp.	P	Rhinocerotidae	*Rhinoceros sinensis* (*Rhinoceros unicornis*)	O, P
	Cricetinae gen. et sp. indet.	O	Suidae	*Sus* sp.	O, P
Arvicolidae	*Allophaiomys pliocaenicus*	P	Cervidae	*Hydropetes* sp.	P
	Proedromys bedfordi	P		*Rusa unicolor* (*Cervus unicolor*)	O, P
Rhizomyidae	*Rhizomys* sp.	O		*Cervus grayi*	P
Hystricidae	*Hystrix* sp.	P, O		*Cervus* sp.	O, P
Muridae	*Niviventer* cf. *N. preconfucianus*	P, O	Bovidae	*Bubalus* sp.	O, P
	Rattus sp.	P, O			

[a] O = Oriental region; P = Palearctic region.

In the 1960s, the upper deposits in the cave were excavated by local farmers who considered the fossilized bones to be "dragon bones" and sold them to drugstores for medicinal use. Paleontologists also collected vertebrate fossils and a molar tooth of *H. erectus* from local farmers who had excavated the cave (Xue, 1987; Xue et al., 1999) (Table 1). In 1995, archaeologists commenced a systematic excavation of the interior and exterior deposits of Longyadong Cave (Wang, 2005; Shaanxi Provincial Institute of Archaeology and Museum of Luonan County, 2008). The interior deposits are 3.4 m thick, with a stratigraphic sequence consisting of the following (LYD section in Fig. 3b): Layer a, 0–0.5 m, soil, disturbed by local farmers; Layer b, 0.5–2.3 m, reddish brown clay; Layer c, 2.3–2.9 m, yellow silt; Layer d, 2.9–3.2 m, yellow medium to fine sand; and Layer e, 3.2–3.4 m, grayish-brown limestone breccia. More than 70,000 lithic artefacts have been excavated from the sediments (Shaanxi Provincial Institute of Archaeology and Museum of Luonan County, 2008) (Fig. 4).

The remains of fire-ash, and "living floors", within which there is abundant evidence of the occupation of hominins, have been identified in these sediments. Trampled surfaces, unworked nodules, anvils, and other brecciated rocks were found in the "living floors", while numerous lithic artefacts and fossil animal remains were concentrated in the central part of the cave (see Supplementary Online Material [SOM] Fig. S1). Lithic artefact refitting analyses show that in the case of the artefacts discovered in Longyadong Cave, nearly one thousand groups of artefacts could be refitted, demonstrating that Longyadong Cave also served as a tool-making site at the time of hominin occupation (Wang, 2005; Shaanxi Provincial Institute of Archaeology and Museum of Luonan County, 2008). The stratigraphy of the sediments outside the cave, designated T1-T5, can be readily correlated with those inside the cave (Fig. 3b).

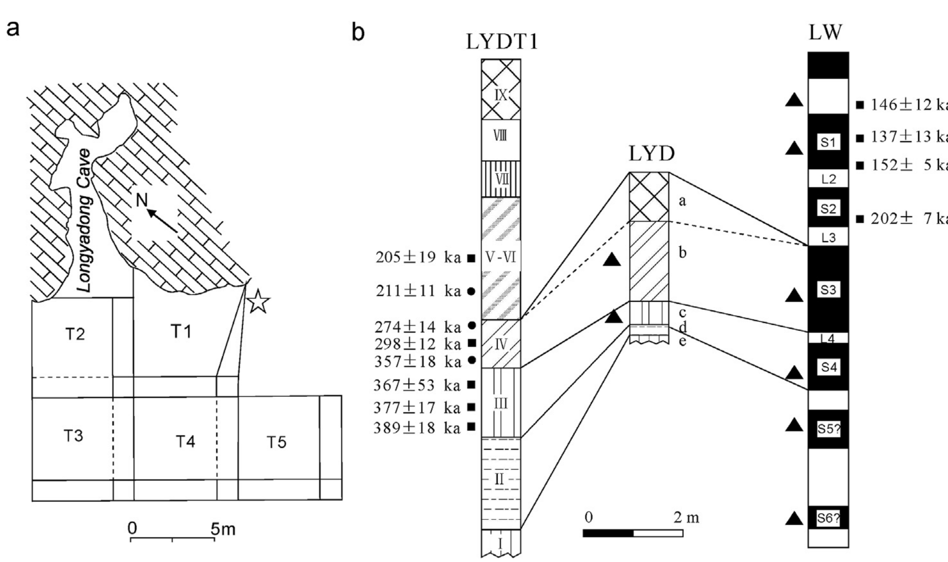

Figure 3. (a) Section plan showing the position of Longyadong Trench 1 (T1) and the LYDT1 loess section (represented by a star). (b) Stratigraphy and dating of the Palaeolithic layers inside Longyadong Cave (LYD), the LYDT1 section and the Liuwan loess-Paleolithic site (LW) (Wang and Huang, 2001; Lu et al., 2007, 2011a; Sun et al., 2013) (black triangles represent the layers and occupation phases of the hominins in Longyadong Cave and at the Liuwan site, black circles represent the dating results of TL, black squares represent the dating results of OSL/TT-OSL).

Figure 4. Burned bones (a and b) and cores and flakes (c to r) excavated from Longyadong Cave. The scale bar represents 2 cm.

In order to minimize the effects of hominin activity on the organic matter preserved in the stratum, and to obtain an integrated picture of the vegetation history close to the Longyadong Cave site, we selected the east wall of T1 for sampling (see Fig. 3a; the position of the section is indicated by a star). Hominin remains have not been discovered at this location and it is also the thickest deposit near the entrance of cave, and thus has the potential for reconstructing natural environmental changes at a high resolution. The section was sampled at 10-cm intervals, yielding a total of 75 samples. The section was designated Longyadong T1 (LYDT1) (Fig. 3a) and the stratigraphy can be summarized as follows: Unit IX, 0–110 cm reddish, disturbed layer, 7.5YR 5/6 light brown, silt, crumb structure, abundant plant roots, contains gravel particles <15 cm in diameter; Unit VIII, 110–200 cm, calcite-cemented layer, 7.5 YR 8/2 light yellow, silt, abundant calcareous cementation, contains gravel particles <15 cm in diameter; Unit VII, 200–290 cm, weakly-developed soil, 7.5YR 6/6 orange, silt to clay, containing abundant gravel-sized particles <15 cm in diameter at the base; Unit VI, 290–380 cm, strongly-weathered soil, 5YR 5/6 light reddish brown, clay-dominated, with scattered gravel particles, rich in iron oxide films; Unit V, 380–520 cm, strongly-developed soil, 5YR4/6 reddish brown, abundant scattered gravel particles with diameters ranging from 1 to >25 cm, clay dominated, with manganese and iron oxide films (a small number of animal fossils were found in the same layer near the entrance to Longyadong Cave); Unit IV, 520–650 cm, strongly-developed soil, 10YR3/3 dark brown, contains a large number of gravel-sized particles with diameters ranging from 1 cm to >20 cm, clay rich in manganese and iron oxides films and with abundant calcareous cementation (the equivalent layer inside Longyadong Cave was rich in fossils and lithic artefacts); Unit III, 650–760 cm, loess, 10 YR 6/6 light yellow brown, silt to sandy loess, containing several gravel-sized particles <10 cm in diameter, abundant calcareous cementation (the equivalent layer inside Longyadong Cave was rich in fossils and lithic artefacts); Unit II, 760–950 cm, sand and gravel layer, 10YR 6/8 light yellow brown, moderate to fine sand in the upper part, abundant gravel-sized particles with diameters <5 cm throughout the lower part (the equivalent layer inside Longyadong Cave contained a small number of fossils and lithic artefacts); Unit I, 950 cm and below, bedrock.

The quantity of artefacts excavated from Longyandong Cave and from T1-T5 changes through time and between different trenches, as shown in Table 2. A correlation of the strata both inside and outside of Longyadong Cave is shown in Figure 3b. Wang and Huang (2001) used thermoluminescence (TL) to date two samples from the main lithic-bearing layer inside Longyadong Cave and one from alluvial deposits outside the cave. The results showed that the age of the middle of the main lithic-bearing layer is about 357 ka and that of the upper part is about 273 ka. Sun et al. (2013) carried out a detailed thermally-transferred optically-stimulated luminescence (TT-OSL) analysis of the eastern wall of Trench 1 outside Longyadong Cave, and obtained similar results to those of Wang and Huang (2001). The combined chronological results indicate that hominins occupied Longyadong Cave between 389 ± 18 and 274 ± 14 ka (Fig. 3b). The stratigraphy and geochronology are correlated with the S4 paleosol, L4 loess and S3 paleosol units of the typical loess-paleosol sequence of the Chinese Loess Plateau.

2.3. The Liuwan loess-Paleolithic site

The Liuwan loess-Paleolithic site is located on the right bank of the Shimen River (Figs. 1 and 2), about 2 km to the northwest of Longyadong Cave. It is a typical lithic site with in situ artefacts found in the exposed loess section, indicating hominin activity at the site at around 600 ka, 400–300 ka and 200–100 ka (Lu et al., 2011a, 2012). The currently recorded artefact layers and their correlation with that of the Longyadong Cave site are shown in Figure 3b. Scattered artefacts were discovered in both loess and paleosol horizons, with a more frequent occurrence in the paleosol layers than in the loess. All of the in situ artefacts discovered so far at the Liuwan site are cores and flakes; in particular, small retouched flake tools dominate the lithic assemblages, as at the

Table 2
Spatial and temporal distribution of number of artefacts excavated from the Longyadong site (modified from Shaanxi Provincial Institute of Archaeology and Museum of Luonan County, 2008).[a]

Lithic units	LYD	T1	T2	T3	T4	T5	Total
Disturbed soil (IV)	3993	18	25	2	0	0	4038
Reddish brown clay (IV)	45,953	2452	1541	57	172	41	50,216
Yellow silt (III)	15,745	304	146	539	42	0	16,776
Yellow medium to fine sand (II)	4663	1148	404	68	38	0	6321

[a] Temporal data in rows is temporal and spatial data in columns. LYD is the trench inside Longyadong Cave and T1 to T5 are trenches outside the Longyadong Cave (see Fig. 3).

Longyandong Cave site. Zhang et al. (2009) conducted $\delta^{13}C_{SOM}$ measurements of part of the loess deposits from this site and concluded that $\delta^{13}C_{SOM}$ can be used as a proxy indicator of vegetation change; however, they did not link their results with hominin environments. For the present study, we obtained samples from the Liuwan loess-Paleolithic section at 10-cm intervals for $\delta^{13}C_{SOM}$ analysis and carefully related the results to the Paleolithic layers. A total of 100 samples were analyzed.

2.4. Organic stable carbon isotope analysis

The samples were dried at 40 °C for 48 h and then passed through a <250 μm sieve in order to remove coarse rock particles and plant fragments. The fine fraction was then ground to 200-mesh size with an agate mortar. Carbonate was removed by reaction with 10% HCl, and then the samples were repeatedly rinsed with distilled water to pH ≈ 7 and then dried at 50 °C for isotope analyses. The carbon isotope composition was determined using an isotope ratio mass spectrometer (Delta Plus; Finnigan MAT). Carbon isotope data are expressed as $\delta^{13}C$, with $\delta^{13}C = (R_{sample}/R_{standard}) - 1$, where R is the $^{13}C/^{12}C$ ratio relative to the Vienna Pee Dee Belemnite (VPDB) standard.

3. Results

The $\delta^{13}C_{SOM}$ values of the LYDT1 profile are shown in Figure 5a. The values range from −28.5‰ to −23.5‰ with a mean of −25.7‰. Except for several $\delta^{13}C_{SOM}$ samples from the bottom gravel layer that

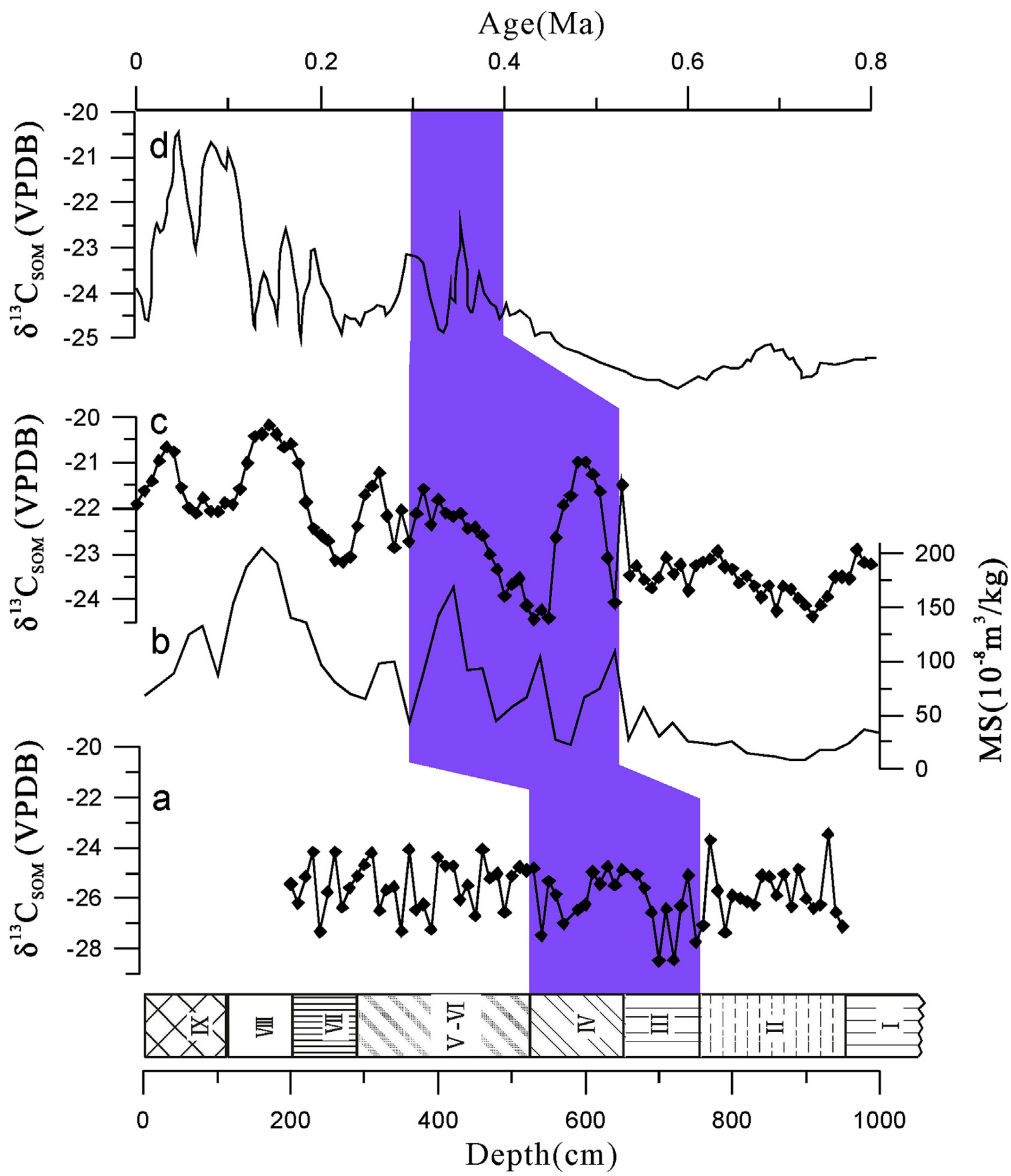

Figure 5. Results of $\delta^{13}C_{SOM}$ analyses of the LYDT1 and Liuwan sections. a: $\delta^{13}C_{SOM}$ record of the LYDT1 section; b: magnetic susceptibility (MS) record of the Liuwan loess section which is an indicator of East Asian monsoonal changes (Lu et al., 2007, 2011a, 2011b, 2012) in the study region; c: $\delta^{13}C_{SOM}$ record of the Liuwan loess-paleosol sequence; d: $\delta^{13}C_{SOM}$ record of the Weinan loess-paleosol section (Sun et al., 2012), located in the southern margin of the Chinese Loess Plateau (location shown in Fig. 1b). The purple bars indicate correlation of the lithic layers of the Longyadong Cave site with that of the Liuwan site and the contemporary loess deposits of the Weinan loess-paleosol section. The $\delta^{13}C_{SOM}$ changes in Liuwan correlate with coeval deposits in the northern steppe lands of the Chinese Loess Plateau, where, for example, a distinct increase in C_4 grasses occurred at the beginning of the formation of the S4 paleosol; in contrast, the $\delta^{13}C_{SOM}$ values of LYDT1 are relatively stable especially from Unit IV. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reached −23.5‰, most of the values range from −27.4‰ to −24.8‰. Unit III is a loess layer and the carbon isotope values average −26.6‰. The $\delta^{13}C_{SOM}$ values increase at the transition from Unit III to the Unit IV paleosol layer and then change to more positive values, which are relatively stable with a range from −24.1‰ ~ −27.3‰, and a mean of −25.5‰.

The $\delta^{13}C_{SOM}$ values of the loess deposits in Liuwan (Fig. 5c) range from −24.4‰ to −20.2‰, which is a similar range to that observed in the central Chinese Loess Plateau (−24.5‰ to −16.9‰; e.g., Liu et al., 2002, 2005; Zhang et al., 2009, 2015). In contrast to the LYDT1 section, in which the $\delta^{13}C_{SOM}$ values fluctuate within a more negative range, the $\delta^{13}C_{SOM}$ values in the Liuwan loess-paleosol sequence exhibit large fluctuations within a more positive range. In addition, the $\delta^{13}C_{SOM}$ and magnetic susceptibility records correspond with that of the Chinese Loess Plateau in terms of glacial–interglacial alternations (Lu et al., 2007; Zhang et al., 2009) (Fig. 5b–d).

4. Discussion

4.1. Organic matter sources of the LYDT1 section

The LYDT1 section is primarily composed of silt and clay particles, similar to the loess-paleosol deposits in the Luonan Basin. This indicates that the particles have a distal source and have been transported by wind from northern China (Zhang et al., 2012). There are four to five distinctly red brown/brown, almost parallel soil layers in the LYDT1 section and no fluvial bedding or laminations were identified, except for the fluvial sediments at the base of the section. About 10%–50% poorly sorted and angular limestone fragments were randomly distributed in the silt and clay matrix, indicating that the particles are probably derived from weathering of the bedrock directly above the LYDT1 section. Dating results indicate that the sediments of the section accumulated slowly from the Middle Pleistocene onwards (Wang and Huang, 2001; Sun et al., 2013). The section contains several well-developed soil layers and thus the organic matter content is probably derived mainly from plants growing in the immediate vicinity, or transported a short distance by surface runoff.

4.2. Implications of the $\delta^{13}C_{SOM}$ variations

Terrestrial higher plants can be divided into three categories according to their photosynthetic pathway: namely C_3, C_4 and CAM, with $\delta^{13}C$ values averaging −27‰ and −12‰ for C_3 and C_4 plants, respectively, while CAM plants have intermediate values (Deines, 1980; Cerling et al., 1993). CAM plants, which usually occur in deserts and include cacti and other succulents, are not important in the study area and therefore the soil organic carbon stable isotopic ratios can be used to identify the type of vegetation in terms of C_3 and C_4 plants.

The $\delta^{13}C$ of C_3 plants in northern China ranges from −21.7‰ to −30‰ with a mean of −26.7‰, and the $\delta^{13}C$ of C_4 plants ranges from −10‰ to −15.8‰ with a mean of −12.8‰ (Liu et al., 2005; Wang et al., 2008a); in addition, there is a 1‰–3.49‰ $\delta^{13}C$ positive bias during plant burial and degradation (Melillo et al., 1989; Balesdent and Mariotti, 1996; Cerling et al., 1997; Wei et al., 1998; Chen et al., 2010). On this basis, the $\delta^{13}C$ values at Longyadong Cave site reveal a C_3-plant-dominated vegetation during the period of formation of the deposit.

C_3-dominated vegetation is likely to consist of C_3 grassland, sparse C_3 woody plants with a C_3 grass understory, or C_3 forest/woodland. In the warm temperate to subtropical zone of China, the climate in the warm season enables the growth of C_4 plants (Zhang et al., 2003; Wynn and Bird, 2008). Therefore, if the vegetation consisted of open grassland or woody grassland, C_4 grasses would have comprised a significant proportion (Liu et al., 2002; Zhang et al., 2015). Accordingly, the C_3-vegetation-dominated community in the Luonan Basin may have been closed C_3 woodland (including shrubland and scrub) or forest. Thus, from ~400 ka the vegetation at the Longyadong Cave site and the surrounding areas was most likely to have been C_3 woodland, based on their negative $\delta^{13}C$ values. In contrast, the $\delta^{13}C_{SOM}$ at Liuwan ranges from −24.5‰ to −20.2‰, which is distinct to that of the LYDT1 section (see SOM Fig. S2) and falls within the range of the deposits of the Chinese Loess Plateau (−24.5‰ and −16.9‰; e.g., Liu et al., 2005; Zhang et al., 2009, 2015). This indicates that the Liuwan site comprised C_3 trees alongside C_3 grass and C_4 grass mixed grassland.

Palynological data obtained from loess deposits at the Shangzhou site (Fig. 1), 30 km west of the Luonan Basin, reveal that over the past ~600 ka the pollen assemblages included woody taxa such as *Quercus*, *Pinus*, *Castanea* and *Betula* mixed with herbaceous taxa such as *Artemisia*, Compositae and Chenopodiaceae (Lei, 2000). Thus, our results indicate that the woodland/grassland mixed vegetation revealed by pollen data from the Eastern Qinling Mountains was not distributed homogeneously. Patches of broad-and needle-leaf woodland occurred at places such as the Longyadong Cave site, whereas the landscape in areas such as Liuwan was occupied by open grassland or woody grassland. This vegetation mosaic probably resulted largely from spatial variations in soil properties, topography and landforms of the Luonan Basin. Woody species usually covered the hill tops, slopes and the vicinity of river banks, while grassland usually developed on the river terraces, which were mantled by thick loess deposits. The faunal assemblages of the Luonan Basin (Table 1) include mammals typical of grassland (e.g., *Equus, Ochotona, Eospalax, Bubalus,* Cricetinae), forest edge or scrub (e.g., *Cervus* (*Sika*)*, Hystrix, Aeretes, Martes*), forest (e.g., *Sciurotamias, Rhizomys, Niviventer,* mastodonts, *Tamiops, Callosciurus, Stegodon, Ailuropoda, Ursus*) and riparian habitats (e.g., *Rhinoceros, Bubalus, Rusa, Hydropetes*). This provides another line of evidence that the Luonan Basin contained forests, grassland and large water bodies over 400–300 ka.

The $\delta^{13}C_{SOM}$ values of the Middle Pleistocene paleosol units at Liuwan are more positive than those of the loess, indicating a relationship between denser C_4 grasses and paleosol development during warmer climate phases. These features are correlated with coeval deposits in the northern steppe lands of the Chinese Loess Plateau, where, for example, a distinct increase in C_4 grassland at the beginning of the S4 paleosol formation was noted (as indicated in Fig. 5c and d). In contrast, the LYDT1 site had a consistent woody plant cover (as indicated in Fig. 5a), although there may have been a change in the composition of the woodland from *Quercus* and *Castanea* dominated in interglacial periods to *Betula* and *Pinus* dominated in glacial periods (Lei, 2000).

4.3. Implications for hominin occupation of northern China

Most of the evidence for hominin occupation in northern China is likely to fall within interglacial periods, and it has been argued that hominins would have struggled to maintain continuous occupation of relatively high-latitude regions such as the Nihewan Basin (Louys and Turner, 2012). A population model of 'source and sink' for hominin adaptation and distribution in Pleistocene Asia has been proposed (Dennell, 2009; MacDonald et al., 2012; Louys and Turner, 2012), whereby tropical, lower-latitude regions maintained continuous 'source' populations (i.e., acted as refugia) and higher latitude regions, such as northern China, would have received hominin groups when environmental conditions were favorable during interglacials. The Luonan Basin is situated in the

Eastern Qinling Mountains, which separate the Luonan Basin from the northern Chinese Loess Plateau and act as a biogeographic barrier between the subtropics to the south and temperate vegetation to the north. Thus, our investigated sites are probably located at the northern-most margin of the biogeographic subregion that incorporates southern China, Vietnam, Laos, Cambodia, Myanmar, and parts of Thailand, which may have provided a long-term residence in Indochina for Pleistocene hominins (Louys et al., 2009).

That the Luonan Basin may have been at the edge of the 'source' region for southeast Asian hominins is supported by the faunal assemblage of Longyadong Cave (Table 1), which is warm temperate to subtropical, and includes taxa typical of both the Palearctic and Oriental regions (Xue et al., 1999). In addition, the dating results for in situ lithic artefacts in the loess deposits reported herein indicate that hominins could have continuously occupied the Eastern Qinling Mountains from the Early to the Middle Pleistocene. Hominins appear to have densely occupied the entire South Luohe River valley during the intervals 800–600 ka, 400–300 ka and 200–100 ka (Lu et al., 2007, 2011a, 2011b, 2012). The TL and TT-OSL dating results for the Longyadong Cave site, together with the density of excavated in situ lithic artefacts and other hominin remains, demonstrate that Longyadong Cave was continuously used, from full interglacial to full glacial, by hominins as a living space and for tool making during 400–300 ka (Wang and Huang, 2001; Sun et al., 2013). The stone knapping techniques used for the lithic assemblages excavated from Longyadong Cave and the recently discovered in situ artefacts from Liuwan are mainly hard hammer direct percussion or bipolar flaking techniques (Fig. 4), similar to the lithic assemblages in Nihewan (Pei, 2002) and Zhoukoudian (Wu et al., 1985) in the Pleistocene. This may indicate that Luonan *H. erectus* was part of the northern China hominin group, but this interpretation on the basis of lithic assemblages may be incorrect (Moore and Brumm, 2007; Lycett and Norton, 2010) and needs further evidence to clarify.

If hominins continuously occupied the Luonan Basin on a glacial–interglacial time scale and flourished during several periods, it is likely that the paleoenvironment of the area was an important contributory factor. The high concentration of Middle Pleistocene archaeological remains in Longyadong Cave suggests that the woody patches of vegetation in the Luonan Basin were probably attractive to hominins. Compared with northern China and the Chinese Loess Plateau, the climate in the Luonan Basin was relatively warm and stable during the glacial–interglacial cycles of the Middle Pleistocene (Lei, 2000; Wu et al., 2004; Ao et al., 2010; Cai et al., 2015). Magnetic susceptibility (Lu et al., 2007, 2011a, 2012), grain-size and geochemical element analyses (Zhang et al., 2012) of Liuwan and other loess sites in Luonan Basin indicate that the Qinling Mountains acted as a barrier to the strong winter monsoon, enhancing the suitability of the environment of the Luonan Basin for hominins. It is also entirely possible that the Luonan Basin acted as a refugium for hominins, per the source and sink model. The results of our stable carbon isotope studies of Longyadong Cave and Liuwan site indicate that in the Middle Pleistocene, the Luonan Basin was occupied by a mosaic of grassland/woody-grassland mixed with woodland/forest, habitat often associated with hominin occupation (e.g. Elton, 2008; Louys and Turner, 2012). In addition, there was the consistent occurrence of patches of woody plants at sites such as Longyadong Cave. In contrast, northern China was experiencing an increasing trend of drying and cooling, with resulting long-term change in the vegetation to a steppe grassland from 0.6 to 0.4 Ma (Wu et al., 2004; Cai et al., 2015), argued to have been less suitable habitat for Middle Pleistocene hominins in glacial periods (Louys and Turner, 2012).

5. Conclusions

Our analyses of organic stable carbon isotopes from Longyadong Cave and Liuwan in the Luonan Basin, together with previous faunal and pollen studies, demonstrate that from 400 to 300 ka hominins were associated with an environment consisting of a mosaic of woody plants and grassland, in a generally warm and stable environment. Woody vegetation patches were probably attractive to hominins, and indeed the palaeoenvironment of the Luonan Basin seems consistent with relatively 'typical' hominin habitats in the early and middle Pleistocene. The environmental heterogeneity of the Luonan Basin in the Middle Pleistocene means that it could have supplied a diverse range of resources, including food and water, for hominins, who also appear to have been amply supplied with raw materials for lithic tools. These factors were probably instrumental in allowing hominins to occupy the Luonan Basin throughout interglacial and glacial periods, and we argue that the Luonan Basin potentially served as a refugium for hominin occupation in northern China during the Middle Pleistocene.

Acknowledgements

We thank Prof. Sarah Elton, the Associate Editor and two anonymous reviewers for their helpful comments, which significantly improved the quality of this paper. We thank Dr. Jan Bloemendal, Dr. Zhaoqun Zhang and Mathew Fox for their help in editing the manuscript. We are grateful to Shuangwen Yi, Xuefeng Sun, Quanyu Liu, Xiaoyong Wang, Xianyan Wang, Fang Lei, Jie Li for their help in the field and the laboratory. This research was supported by the National Natural Science Foundation of China (Grant Nos. 41401220, 41472138 and 41472026), the Global Change Program of the Ministry of Science and Technology of China (Grant No. 2016YFA0600503) and the Australian Research Council Discovery Project (Grant No. DP0665250).

Supplementary Online Material

Supplementary online material related to this article can be found at http://dx.doi.org/10.1016/j.jhevol.2017.01.011.

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