HUMAN-ANIMAL INTERACTIONS IN PREHISTORIC CHINA

EDITED BY: Shuangquan Zhang, Manuel Domínguez-Rodrigo,
Dongju Zhang and Yue Zhang
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HUMAN-ANIMAL INTERACTIONS IN PREHISTORIC CHINA

Topic Editors:
Shuangquan Zhang, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences (CAS), China
Manuel Domínguez-Rodrigo, University of Alcalá, Spain
Dongju Zhang, Lanzhou University, China
Yue Zhang, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences (CAS), China

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EDITORIAL
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Editorial: Human-Animal Interactions in Prehistoric China

Shuangquan Zhang[1,2]*, *Manuel Domínguez-Rodrigo*[3], *Dongju Zhang*[4] *and Yue Zhang*[1,2]

[1]Key Laboratory of Vertebrate Evolution and Human Origins, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, China, [2]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, China, [3]Department of History and Philosophy, University of Alcalá de Henares, Alcalá de Henares, Spain, [4]Key Laboratory of Western China's Environmental Systems (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou, China

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Editorial on the Research Topic

Human-Animal Interactions in Prehistoric China

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Edited and reviewed by:
Robert R. Reisz,
University of Toronto Mississauga, Canada

Correspondence:
Shuangquan Zhang
zhangshuangquan@ivpp.ac.cn

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The study of human-animal relations is one of the most dynamic and intriguing topics in archaeology and anthropology (Serjeantson, 2000; Russell, 2012). Over the past decades, our understanding of the deep past societies and the evolutionary trajectory of prehistoric human behaviors has advanced tremendously, fueled partially by the important finds of animal remains from around the world, and also by the prompt application of a plethora of innovative analytical methodologies to key questions, and at key sites (Espigares et al., 2019; Mannermaa and Kirkinen, 2020; d'Errico, 2021; Domínguez-Rodrigo et al., 2021; Domínguez-Rodrigo et al., 2022). Nevertheless, it seems equally clear that on the one hand, the overwhelming majority of achievements in this regard have been obtained from sites in Africa, Europe and near Eastern Asia, with sites from East Asia generally under-investigated; and, on the other, most researchers in China are basically prone to interpret the bones from the archaeological sites as either reflecting environmental issues or resources situated within the landscapes, irrespective of the diverse and complex nature of the interactions between prehistoric humans and their contemporary animals. The research topic for this special issue aims, thus, to compensate such an imbalance in this sub-field of archaeology, and further augment our understanding of the deep-time societies, by bringing together a set of research papers which may potentially highlight a full spectrum of human–animal relationships in China, the key region in East Asia archaeology. Works published in the current research topic provide a variety of perspectives on this shared theme.

As a burgeoning sub-discipline in prehistoric archaeology, stable isotope analyses of faunal remains has been widely used to study environments, ecologies, and animal husbandry and management practices in prehistoric societies of China (Barton et al., 2009; Barton et al., 2020). Three articles from this collection address human-animal relations from such a perspective. In their analysis of stable isotope ratios of the fossil teeth at Madigou (ca. 1.2 Ma), a newly excavated early Pleistocene site in the Nihewan Basin, Xu et al. argue that the mammal species accumulated at the site occupied a relatively broad niche, ranging from open grassland to closed forest; isotopic evidence also indicates that hominins might have had experienced substantial regional dry/cold and warm/wet fluctuations and seasonal variations, which probably would have exerted some detectable impacts on the stone tool technological variabilities previously recorded at the site (Pei et al., 2019). With an aim to explore the nature of human–animal interactions during the Eastern Zhou Dynasty (770–221 BCE), Cui et al. performed a somewhat in-depth analysis of the isotopic composition of carbon and nitrogen, extracted from both human and animal remains at the Chongpingyuan site, Shaanxi Province of China. The result demonstrates that the inhabitants at the site survived mainly on an agro-pastoral economy, with millet agriculture as their economic mainstay. In addition, it seems somewhat clear that people buried with abundant material objects probably have consumed more animal protein, an observation reminiscent of defined social hierarchy in ancient societies (Grant, 2002). The third analysis, performed by Lyu et al. on the faunal bones from the Bronze Age (c. 2000–256 BC) to the Liaojin Dynasties (907–1234 AD) of northeastern China, indicates that domesticated pigs at the site were managed in a free-ranging manner, which is strikingly different from the husbandry strategy adopted by people at the contemporaneous sites in the nearby West Liao River Basin region (Dong et al., 2016).

Two articles express a specific concern with the human-animal relations clearly arising from another perspective—animals for tools, which is one of the most promising areas in the prehistory of China, but rarely touched on seriously in the literature (Zhang et al., 2016; Doyon et al., 2018; Doyon et al., 2021). Ma and Doyon provide an up-to-date synthesis of the finds of Pleistocene osseous tools across mainland China and further argue that the cultural trajectories documented in the evolution of bone technologies in China are grossly comparable to those identified in other regions of the world. Xie et al. provide a case study analysis of the scapular shovels of the early Hemudu Culture (7000–6000 BP) in the southern Yangzi Delta and reveal an interesting binary system from the site, in which a loose quality control was mixed with a marked raw material, and stylish preference in manufacturing of the community's iconic implements; this fact, to a certain extent, argues for a knowledge and skill transmission for osseous implement production in prehistoric society of China.

Among the remaining articles, Huang et al. report the result of an XRD analysis of 23 fossil bones, retrieved from the new excavations at Zhoukoudian Locality 1, the type section of Asia *Homo erectus* fossils. Being consistent with macroscopic observations, the analysis indicates that at least 15 bones were heated above 600°C. This re-fuels the hot debate on the issue of hominin use and maintenance of fire in the cave (Weiner et al., 1998; Gao et al., 2017). The strength of Song et al.'s article lies in the symbolic dimensions of the human-animal relations. By focusing specifically on the diachronic changes of use and production of the OES beads and pendants from Shizitan, an Upper Paleolithic site complex in northern China, Song et al. provide fresh insights into potential roles that OES ornaments may have had played in behavioral adaptations of hunter–gatherers in coping with challenges posed by climatic fluctuation and environmental deterioration from LGM through the Terminal Pleistocene in northern China. Klementiev et al. present a paleontological article based mainly on the latest regional finds of extinct Pleistocene *Camelus knoblochi* from the Tsagaan Agui cave, Mongolia, but with a somewhat intriguing discussion of human-camel interactions in the Paleolithic period of both Mongolia and China. Zhang et al. provide a zooarchaeological analysis of a sika deer (*Cervus nippon*) assemblage from Tianluoshan, a Neolithic site in the lower Yangtze River region of southern China and document an exemplary case of sustainable hunting strategy adopted by prehistoric humans. The last article contributed by Zhang et al., reveals a mixed pastoral system and millet cultivation at around 4,000–3,700 cal yr BP at the Zhukaigou site, which may have had enhanced the adaptability of local population and thus prompted their occupation of the relatively arid environment of the monsoon marginal area of northern China.

To sum-up, the articles presented here have expanded our understanding of some important areas related to human-animal interactions in prehistoric China. Nonetheless, there still exist some remarkable imperfections with this themed collection. For instance, as zooarchaeologists, we are compelled to be concerned with site formation processes, as they are at the core of and the prerequisite for a better understanding of the faunal remains from the archaeological sites, especially those of the Paleolithic period (Lyman, 1994; Domínguez-Rodrigo et al., 2007; Fernández-Jalvo and Andrews, 2016); the sheer deficiency of taphonomic contributions to this research topic is, thus, a surprise. More importantly, in light of the newly emerging of copious discourses on epistemological and ontological issues surrounding animals' status in relation to human societies (Overton and Hamilakis, 2013; Boyd, 2017; Oma and Goldhahn, 2020), the analytical framework adopted by most articles in this collection is fundamentally anthropocentric. As argued by Overton and Hamilakis (2013), the adoption of a new non-anthropocentric framework in the explorations of the interaction between human and animals does not denote a rejection of either the 'environmental', 'economic' or the 'subsistence' perspective in conventional zooarchaeological paradigms, but will instead increase the richness of our interpretative insights into the analysis of the animal bones from the archaeological sites across the world. This transformed social zooarchaeology has triggered some groundbreaking achievements in recent years, and is thus one of the alternative avenues which we Chinese researchers engaged on the subject of human-animal relations in prehistoric period, specifically in its latest part should pursue in future studies.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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ORIGINAL RESEARCH
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Pastoralism and Millet Cultivation During the Bronze Age in the Temperate Steppe Region of Northern China

Yaping Zhang[1,2]*, Ying Zhang*[3]*, Songmei Hu*[4]*, Xinying Zhou*[1,2,5]*, Linjing Liu*[6]*, Junchi Liu*[1,5]*, Keliang Zhao*[1,2,5]** and Xiaoqiang Li*[1,2,5]

[1]*Key Laboratory of Vertebrate Evolution and Human Origins of the Chinese Academy of Sciences, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, China,* [2]*Department of Earth Science, University of the Chinese Academy of Sciences, Beijing, China,* [3]*Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China,* [4]*Shaanxi Provincial Institute of Archaeology, Xi'an, China,* [5]*CAS Center for Excellence in Life and Paleoenvironment, Beijing, China,* [6]*Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, Shijiazhuang, China*

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Edited by:
Shuangquan Zhang,
Institute of Vertebrate Paleontology and Paleoanthropology (CAS), China

Reviewed by:
Qianli Sun,
East China Normal University, China
Taylor Hermes,
Max Planck Institute for Evolutionary Anthropology, Germany
Li Liu,
Stanford University, United States

***Correspondence:**
Keliang Zhao
zhaokeliang@ivpp.ac.cn

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Eastern and Western Asia were important centers for the domestication of plants and animals and they developed different agricultural practices and systems. The timing, routeway and mechanisms of the exchanges between the two centers have long been important scientific issues. The development of a mixed pastoral system (e.g., with the rearing of sheep, goats and cattle) and millet cultivation in the steppe region of northern China was the result of the link between the two cultures. However, little detailed information is available about the precise timing and mechanisms involved in this mixture of pastoralism and millet cultivation. To try to address the issue, we analyzed the pollen, fungal spores and phytolith contents of soil samples from the Bronze Age Zhukaigou site in the steppe area of North China, which was combined with AMS ^{14}C dating of charcoal, millet and animal bones. A mixed pastoralism and millet agricultural system appeared at the site between 4,000 and 3,700 cal yr BP, and the intensity of animal husbandry increased in the later stage of occupation. Published data indicate that domestic sheep/goats appeared across a wide area of the steppe region of northern China after ~4,000 cal yr BP. A comparison of records of sheep/goat rearing and paleoclimatic records from monsoon area in China leads us to conclude that the mixture of pastoralism and millet cultivation was promoted by the occurrence of drought events during 4,200–4,000 cal yr BP. Moreover, we suggest that mixed rainfed agriculture and animal husbandry increased the adaptability and resilience of the inhabitants of the region which enabled them to occupy the relatively arid environment of the monsoon marginal area of northern China.

Keywords: Zhukaigou site, 4.2 cal kyr BP, sheep/goat rearing, rainfed agriculture, human adaptation

INTRODUCTION

The domestication of plants and animals greatly enhanced human adaptability to environmental changes and at the same time profoundly affected human cultural development and ultimately large urban centers (Zeder, 2008; Lv et al., 2009; Yuan, 2010). Western Asia, Eastern Asia and Central America were important centers for the early domestication of plants and animals. Barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), cattle (*Bos taurus*), sheep (*Ovis aries*) and goats (*Capra aegagrus*) were originally domesticated in Western Asia. Rainfed agriculture, rice cultivation, together with the domestication of dogs (*Canis familiaris*) and pigs (*Sus domestica*) originated in Eastern Asia (pigs were also domesticated in SW Asia), while maize and alpacas were first domesticated in Central America (Cruz-Uribe, 1987; Fuller et al., 2010; Yuan, 2010; Lv, 2018). The exchange and mixture of different agricultural systems during the Holocene enabled humans to adapt to different environments and to environmental fluctuations. The timing, pathways and mechanisms of early agricultural cultural interactions (also known as food globalization) have long been considered an important topic in archaeology and global changes (Jones, 2007; Liu et al., 2019).

The Eurasian steppe is an important routeway of cultural exchanges between the East and West (Frachetti et al., 2012; Qu et al., 2020). Botanical archaeological research has revealed that wheat and barley cultivation spread to the Altay region of the Eurasian steppe as early as 5,200 cal yr BP (Zhou et al., 2020), and subsequently appeared in the Hexi Corridor and in the Shandong Peninsula in China between 4,300 and 4,000 cal yr BP (Dodson et al., 2013; Long et al., 2018). Millet cultivation was practiced in southeast Kazakhstan in Central Asia at ~4,700 cal yr BP, and then spread westward at ~4,000 cal yr BP (Betts et al., 1995; Jones, 2007; Miller et al., 2016; Wang et al., 2017; Hermes et al., 2019).

The spread of pastoralism represented by sheep/goat and cattle rearing provides important evidence for cultural interactions between the East and West. Domesticated sheep/goats appeared in the Mongolian steppe and then spread eastward and southward by at least 5,200 cal yr BP (Li and Song, 2018; Wilkin et al., 2020). Domestic cattle rearing can trace back to 5,500–5,300 cal yr BP at the Houtaomuga site in Northeast China (Cai et al., 2018). The earliest evidence for sheep rearing in China may be from the Shizhaocun and Hetaozhuang sites in the western Loess Plateau (Yuan, 2010). The context of the cultural layer indicated that the interval of sheep rearing was 5,000–5,600 cal yr BP, but the sheep bone have not yet been directly dated (Yuan, 2010). Two important questions regarding this evidence are how this animal husbandry was introduced to Eastern Asia, and whether it was imported together with wheat or other crops. More specially, the transmission mechanism of these agricultural practices, the timing of the domestication of sheep/goats and cattle, and the routeway of their dispersal are unknown.

The steppe of northern China is located in the eastern part of the Eurasian steppe belt, and it includes the steppe regions of the Northeastern Plain, the Inner Mongolia Plateau, the Ordos Plateau, and the Loess Plateau. Overall, these regions have long had a mixed agricultural and pastoral economy due to the arid and semiarid climate, with millet cultivation and animal husbandry (e.g., sheep, goats and cattle) being major components. The combination of millet cultivation, pig rearing and hunting and gathering was the dominant subsistence strategy of the region since before the mid-Holocene, which differs substantially from the agriculture practiced in the region today (Hu and Sun, 2005). The rearing of sheep, goats and cattle, together with other forms of animal husbandry, began to appear in the middle and late Holocene, eventually resulting in the development of a mixed agricultural system based on rainfed cultivation and animal husbandry. The development of this agro-pastoral system enabled the inhabitants of the region to adapt to its climate from wet to dry. However, there is a lack of detailed research on the relationship between the timing of the development of this agro-pastoral system and the environmental background (Zhao, 2006).

To attempt to address this knowledge gap we studied a section at the Zhukaigou (ZKG) site in the steppe region of northern China. Analyses of pollen, phytoliths, and the stable isotope composition of animal bones, combined with AMS^{14}C dating and reference to published botanical and zoological archaeological evidence, enable us to determine the timing of the appearance of this mixed agricultural economy in the study area. We also compare the findings with records of the regional climatic and environmental evolution and develop a possible link between the development of agro-pastoralism and climate change.

STUDY REGION

The Bronze Age site of ZKG is located in the eastern part of the Ordos Plateau in southern Inner Mongolia (**Figure 1**). The archaeological site was discovered in 1974, and so far it has been excavated four times. Archaeological excavations have revealed the remains of houses, ash pits, tombs, other relics, a large amount of pottery, stone artifacts, numerous bone artifacts, bronze artifacts, and abundant animal remains. The pottery type series include tripod jars, basins, pots, spindle whorls and so on. The stone artifacts include axes, chiels, knives and adzes. The Bronze ware includes the famous Ordos bronze dagger, a bronze knife and ornaments (Institute of Cultural relics and Archaeology, Inner Mongolia Autonomous region, 2000). The domestic animal remains excavated at the site include pigs, sheep, cattle and dogs, and wild animals include badger (*Meles*), bear (*Ursus* sp.), leopard (*Panthera pardus*), roe deer (*Capreolus*), red deer (*Cervus elaphus*), and goral (*Noemorhedus goral*) (Huang, 1996). In recent years, the study of archaeobotany has revealed that the inhabitants of the ZKG site grew common millet (*Panicum miliaceum*) and foxtail millet (*Setaria italica*) (Bao et al., 2018).

Most of the Ordos Plateau, where the ZKG site is located, is a mixed agricultural-pastoral area, while the subsistence strategy in the Mu Us sandy land to the southwest is dominantly animal husbandry. The zonal vegetation is typical steppe dominated by *Stipa bungeana* and *Stipa krylovii*. Due to erosion, desertification

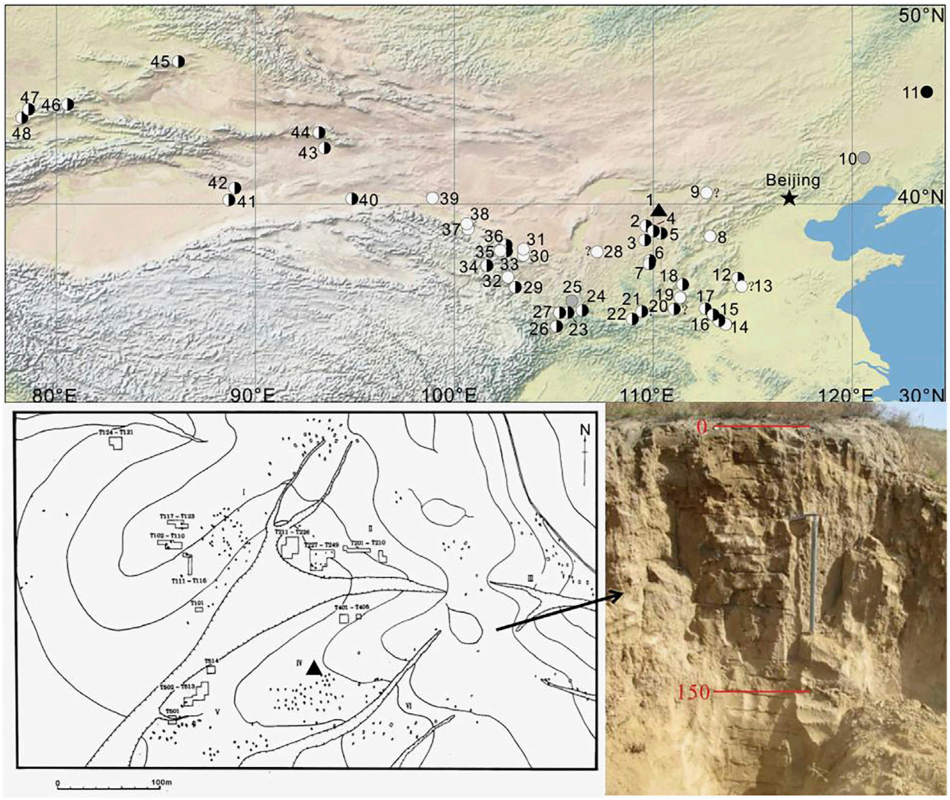

FIGURE 1 | Location of the Zhukaigou site and other sites mentioned in the text. White and black circles indicate sites with the remains of domestic sheep/goat and cattle, respectively. Grey circles indicate sites without the remains of domestic sheep/goat and cattle. "?" indicates a site where it is uncertain whether the sheep/goat or cattle were domesticated. The sites names represented by the numbers are shown in **Table 1**. The Zhukaigou section and its location in the Zhukaigou site. The location map of Zhukaigou site was cited from the Institute of Cultural relics and Archaeology, Inner Mongolia Autonomous region, (2000).

and long-term human activities, desert vegetation has replaced the native steppe vegetation in most of the area. The main plant taxa are: *Artemisia ordosica*, *Caragana*, *Sabina vulgaris* Ant and Salicaceae. The annual average temperature of the region is 5.3–7.5°C and the annual precipitation is 270–400 mm. The climate is arid and semiarid.

MATERIALS AND METHODS

Stratigraphy of the Zhukaigou Section

The ZKG section (39°6′N, 110°3′E) located in the southern of the site, which is 155 cm-deep (**Figure 1**) and contains evidence of human activities, such as pottery and charcoal. According to the color and structural characteristics of the sediments, the section is divided into four layers: 1) 0–40 cm: Light gray sandy silt with abundant charcoal fragments, large calcium carbonate nodules, and small pebbles. 2) 40–70 cm: Light yellow sandy silt with less charcoal than above; abundant larger calcium carbonate nodules, small gravel clasts and gray clay pottery. 3) 70–100 cm: Light gray sandy silt containing occasional charcoal fragments, small calcium carbonate nodules, pebbles and animal remains. 4) 100–155 cm: Pale yellow sandy silt layer containing a small amount of charcoal, fine gravel and gray clay. The natural soil layer is below the depth of 155 cm. In order to determine the age of the sedimentary section, charcoal and grains of millet were selected at the depths of 145 cm, 105 and 60 cm for AMS ^{14}C dating.

AMS ^{14}C Dating of Domesticated Animal Remains at the ZKG Site

Huang, (1996) suggested that the domesticated animals at the ZKG site consist of pigs, sheep and cattle, and they estimated the age of the remains based on AMS ^{14}C dating of charcoal recovered from the strata. So far, however, there has been no direct AMS ^{14}C dating of the remains of domesticated animals at the site, and therefore we selected animal bones from different cultural periods for AMS ^{14}C dating. The AMS ^{14}C dating was conducted at the Beta Laboratory, United States. The dated samples included two pig bones, two sheep bones and one cattle bone, from different cultural layers. The AMS ^{14}C dating results were calibrated using IntCal20 in OxCal 4.3 software (Reimer et al., 2020).

3.3 Pollen and Phytolith Analysis

Fifteen pollen samples of ~30 g weight were analyzed using conventional heavy liquid separation. A known number of

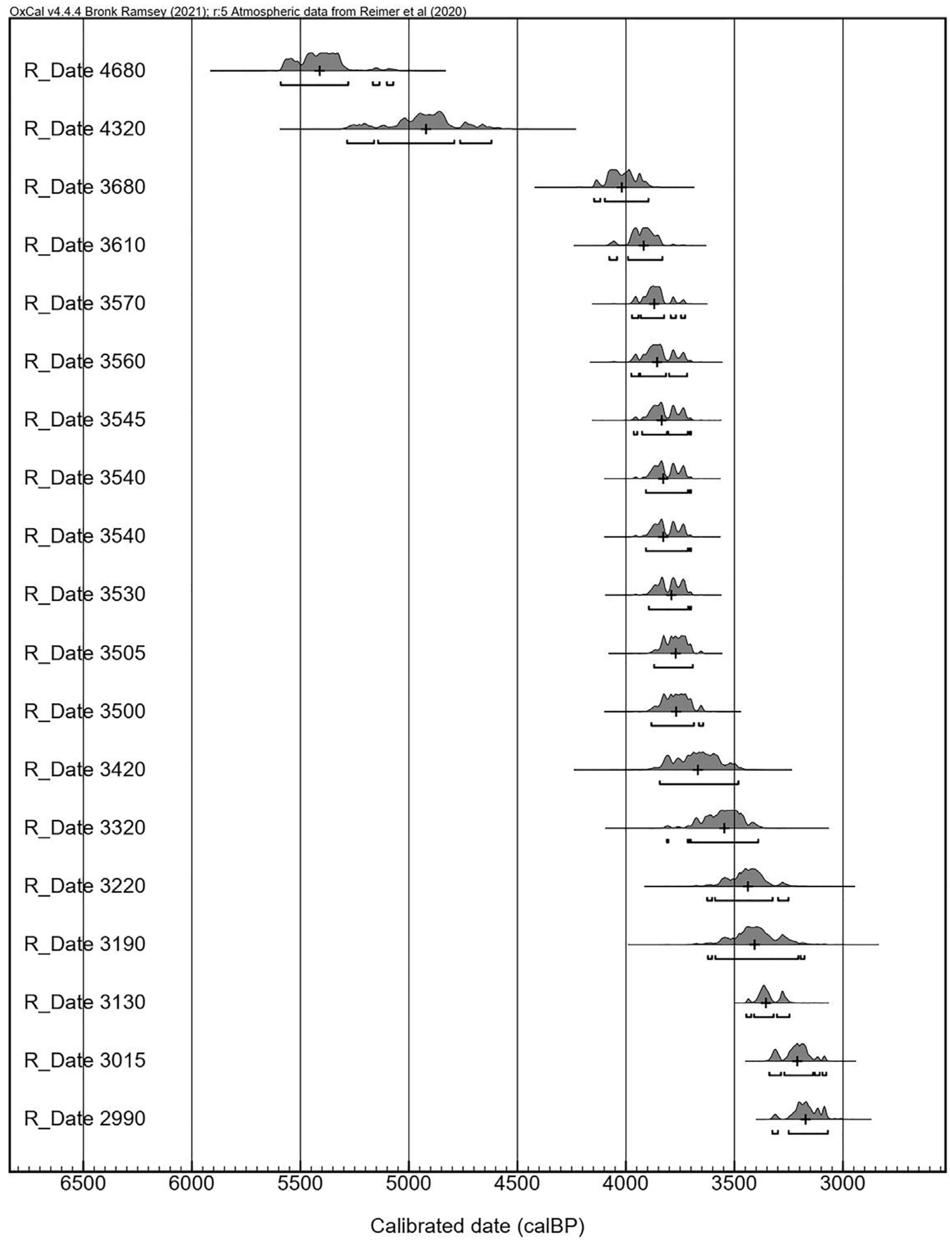

FIGURE 2 | AMS 14C dating results for the samples from the ZKG site. "+" indicates the median age. The ages were determined using OXCAL 4.3 software with the INTCAL20 curve correction (Reimer et al., 2020).

Lycopodium spores was added prior to the preparation to calculate pollen concentrations. The identification of pollen and fungal spores was based on atlases of pollen morphology (Taylor, 1988; Xi and Ning, 1994; Wang et al., 1995; Van Geel et al., 2003; Tang et al., 2016). A pollen and fungal spores diagram was drawn and statistical zonation was conducted using CONISS implemented in Tilia 2.0 (https://www.tiliait.com/). The charcoal content was estimated using point counting. Fifteen samples of ~10 g weight were used for phytolith analysis following the conventional wet oxidation method. Phytoliths were identified with reference to the phytolith key of Wang and Lv (1993), and a phytolith diagram was drawn using Tilia software.

RESULTS

AMS ^{14}C Dating Results

The AMS ^{14}C dating results for the materials from the ZKG are illustrated in **Figure 2** and listed in **Table 1**. The age of charcoal fragments at the depth of 145 cm in the ZKG section is 3,718–3,975 cal yr BP (OZQ360); and that of the depth of

TABLE 1 | The sites names represented by numbers in **Figure 1** and their abbreviations in this study.

Number	Archaeology sites	Abbreviation	Species	Age (cal yr BP)	Reference
1	Zhukaigou	ZKG	*Ovis aries; Bos taurus*	3,247–3,972[a]	This study
2	Muzhuzhuliang	MZZL	*Ovis aries; Bos taurus*	3,800–4,000	Chen et al. (2015)
3	Huoshiliang	HSL	*Ovis aries; Bos taurus*	3,800–4,200	Hu S. M. et al. (2008); Dodson et al., 2014
4	Xinhuacun	XHC	*Ovis aries*; *Bos taurus*	3,820–4,150	Sun et al. (2002)
5	Shimao	SM	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,800–4,300	Hu et al. (2016)
6	Hongliang	HL	*Ovis aries; Capra aegagrus hircus; Bos taurus*	4,186–4,407[a]	Hu, (2021)
7	Jingbianmiaoliang	JBML	*Ovis aries; Capra aegagrus hircus; Bos taurus*	4,151–4,406[a]	Hu, (2021)
8	Youyao	YY	*Ovis aries*	4,000–4,300	Dodson et al. (2014)
9	Shihushan	SHS	*Ovis* sp.	6,000–6,700	Dodson et al. (2014)
10	Xinglonggou	—	—	7,500–8,000	Zhao, (2005)
11	Houtaomuga	—	*Bos taurus*	5,300–5,500	Cai et al. (2018)
12	Yinxu	YX	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,400	Institute of Archaeology, Chinese Academy of Social Sciences, (1994)
13	Baiying	BY	Caprinae	3,500–4,200	Zhou, (1983)
14	Xinzhai	XZ	*Ovis aries/Capra aegagrus hircus*	3,500–3,800	Huang, (2008)
15	Wadian	WD	*Ovis aries; Bos taurus*	3,500–4,300	Lv et al. (2007)
16	Wangchenggang	WCG	*Ovis aries; Bos taurus*	3,700–4,000	School of Archaeology and Museology, Peking University, (2007)
17	Erlitou	ELT	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,500–3,800	Cai et al. (2010)
18	Taosi	TS	*Ovis aries; Bos taurus*	~4,000	Chen et al. (2012)
19	Dongxiafeng	DXF	*Ovis aries*	3,500–3,700	Dodson et al. (2014)
20	Miaodigou	MDG	Caprinae; Bovinae	5,500–6,000	Institute of Archaeology, Chinese Academy of Sciences, (1959)
21	Lingkou	LK	Caprinae; Bovinae	6,100–6,700	Shaanxi Institute of Archaeology, (2004)
22	Kangjia	KJ	*Ovis aries/Capra aegagrus hircus; Bos taurus*	4,000–6,000	Liu et al. (2001)
23	Xishanping	XSP	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,800–4,200	Institute of Archaeology, Chinese Academy of Social Sciences, (1999); Yuan, 2010
24	Qinweijia	QWJ	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,800–4,200	Gansu Task Force, Institute of Archaeology, Chinese Academy of Sciences, (1975)
25	Dadiwan	-	-	7,350–7,800	Liu et al. (2004)
26	Xihelanqiao	XHLQ	*Ovis aries/Capra aegagrus hircus; Bos taurus*	2,877–3,450[a]	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
27	Shizhaocun	SZC	*Ovis aries/Capra aegagrus hircus; Bos taurus*	5,000–5600,3800–4,200	Institute of Archaeology, Chinese Academy of Social Sciences, 1999; Yuan, 2010
28	Haba Lake	HBL	*Ovis* sp.	4,500–4,900	Dodson et al. (2014)
29	Dahezhuang	DHZ	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,400–3,800	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
30	Shuikou	SK	*Ovis aries/Capra aegagrus hircus*	3,932–4,142[a]	Yang et al. (2019)
31	Guojiashan	GJS	*Ovis aries/Capra aegagrus hircus*	3,500–4,400	Yang et al. (2019)
32	Hetaozhuang	HTZ	*Ovis aries*	5,000–5,600	Yuan, (2010)
33	Mozuizi	MZZ	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,073–3,316[a]	Yang et al. (2019)
34	Changning	CN	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,800–4,200	Cai et al. (2010)
35	Lijiageleng	LJGL	*Ovis aries/Capra aegagrus hircus*	3,588–3,810[a]	Yang et al. (2019)
36	Huangniangniangtai	HNNT	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,600–4,400	Wei, (1978)
37	Donghuishan	DHS	*Ovis aries/Capra aegagrus hircus*	3,481–3,823*	Xu and Zhang, (1995)
38	Xihuishan	XHS	*Ovis aries/Capra aegagrus hircus*	3,481–3,823[a]	Yang et al. (2019)
39	Ganguya	GGY	*Ovis aries/Capra aegagrus hircus*	3,362–3,821[a]	Yang et al. (2019)
40	Dadunwan	DDW	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,218–3,442[a]	Yang et al. (2019)

(Continued on following page)

TABLE 1 | (*Continued*) The sites names represented by numbers in Figure 1 and their abbreviations in this study.

Number	Archaeology sites	Abbreviation	Species	Age (cal yr BP)	Reference
41	Xiaohe	XH	*Ovis aries; Bos taurus*	~4,000	Yang et al. (2014)
42	Gumugou	GMG	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,800–3,900	Wang, (1983)
43	Tianshanbeilu	TSBL	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,300–4,000	Wang et al. (2017)
44	Shirenzigou	-	*Ovis aries; Capra aegagrus hircus; Bos taurus*	~2,300	You et al. (2014)
45	Tongtian cave	TTC	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,200–5,200	Zhou et al. (2020)
46	Adunqiaolu	ADQL	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,200–3,850	Cong et al. (2013)
47	Dali	—	*Ovis aries; Capra aegagrus hircus; Bos taurus*	4,700	Hermes et al. (2019)
48	Begash/Tasbas	—	*Ovis aries; Capra aegagrus hircus; Bos taurus*	4,200–4,500	Hermes et al. (2019)

[a]*indicate the ages of the AMS,* ^{14}*C dating of the remains of sheep/goat or cattle bones from the archaeology sites and other ages were deduced from the context of the cultural layer.*

105 cm is 3,700–3,908 cal yr BP (Beta 563,896); the age of carbonized seeds at the depth of 60 cm is 3,700–3,908 cal yr BP (Beta 563,895); and the age of cattle remains is 3,727–3,972 cal yr BP (median age of 3,870 cal yr BP, the same below). The ages of sheep and pig remains from the second cultural stage are 3,700–3,908 cal yr BP (3,828 cal yr BP) and 3,700–3,894 cal yr BP (3,791 cal yr BP). The age of sheep remains from the third cultural stage is 3,247–3,445 cal yr BP (3,355 cal yr BP). The age of pig remains from the fourth cultural stage is 3,070–3,325 cal yr BP (3,172 cal yr BP). Thus, the age range of the remains of domestic animals at the site is 3,070–3,972 cal yr BP. The published AMS ^{14}C ages for the ZKG site are between 4,100 and 3,100 cal yr BP, except for two ages that are older than 4,500 years (**Figure 2**; **Table 2**).

Pollen Analysis

A total of 4,445 pollen grains, comprising 18 families and genera, were identified from the 15 samples analyzed from the ZKG section (**Figure 3**). The main tree pollen types are *Pinus*, *Betula*, *Ulmus* and Fagaceae; and the main shrubs and herb pollen types are *Artemisia*, Chenopodiaceae, *Ephedra*, Asteraceae, Leguminosae, *Tamarix*, *Polygonum*, and Apiaceae. Ferns are rare and include Monoletes, Triletes and Polypodiaceae. The fungal spores are mainly *Sporormiella* and *Srodaria.* The pollen diagram (**Figure 4**) was divided into three zones according to CONISS, and are described below.

Pollen Assemblage Zone I (*Artemisia*-Chenopodiaceae): 155–130 cm. The zone is dominated by herbaceous pollen which is dominated by *Artemisia* (53.7–61.2%; average of 57%), followed by Chenopodiaceae (33.3–43.3%; average of 36.7%. Poaceae is relatively poorly represented (1.5–8.8%; average of 4.3%). The content of *Sporormiella* fungal spores is 0–1.1% (average of 0.6%). The charcoal concentration is low, with an average of 0.9×10^{-2} cm^2 g^{-1}.

Pollen Assemblage Zone II (*Artemisia*-Chenopodiaceae-Poaceae): 130–60 cm. There are substantial changes in the herbaceous taxa compared with Zone I, with a major decrease in Chenopodiaceae (10.4–39.2%; average of 20.8%) and an increase in Poaceae (5.5–49.3%; average of 23.5%). However, *Artemisia* is still well represented (23.9–63.9%; average of 48.4%). The content of fungal spores is slightly higher than in Zone I, including *Sporormiella* (0.0–2.7%; average of 0.8%) and *Sordaria* (0.0–3.6%; average of 0.7%. The concentration of charcoal particles is higher than in the Zone I ($1.2–61.8 \times 10^{-2}$ cm^2 g^{-1}; average of 26.9×10^{-2} cm^2 g^{-1}).

Pollen Assemblage Zone III (*Artemisia*-Chenopodiaceae-Poaceae): 60–0 cm. *Artemisia* (34.7–48.3%, average of 39.6%) and Chenopodiaceae (13.3–26.2%; average of 21.8%) are well represented. The representation of Poaceae (12.5–39%, average of 22.7%) is similar to that of Zone II. There is a substantial increase in the representation of fungal spores, including *Sporormiella* (0–4.5%; average of 1.8%) and *Sordaria* (1.3–3.4%; average of 2.5%). The concentration of charcoal fragments is substantial higher than in Zone II (93–968 $\times 10^{-2}$ cm^2 g^{-1}).

Phytolith Analysis

A total of 9,630 phytoliths were identified in the 15 samples from the ZKG section, comprising 16 taxonomic categories (**Figure 3**). The main morphotypes are: Elongate psilate, Elongate dendritic, Rectangle, Square, Acicular hair cell, Sponge spicules, Saddle, Cuneiform bulliform, Elongate echinate, Tooth type, "Y" type, Fusiform, Bilobate, Triangular prism, and common millet and foxtail millet. The morphotypes for common millet and foxtail millet are "η" and "Ω", repectively (Lv et al., 2009). And they come from husks. There are few other Panicoideae phytoliths in the samples. The phytoliths are dominated by Elongate psilate (25.1–49.9%) and Acicular hair cell (11.2–50.6%). The phytoliths of common millet and foxtail millet occur within the depth interval of 70–135 cm; the lowest representation is 0.2% at a depth of 70 cm and the highest is at 105 cm, representing 33.4 and 41.1% of total phytoliths, respectively. Based on the cluster analysis, the phytolith records can also be divided into three zones (**Figure 5**):

TABLE 2 | ^{14}C dates for the ZGK site.

LabID	Sample ID	Material	^{14}C age (yr BP)	Calibrated age (cal yr BP)	Median age (yr BP)	δ13C ‰	δ15N ‰	C/N	wt.% C	wt.% N	Reference
Beta - 572,544	T246-5	Cattle bone	3,570 ± 30	3,727–3,972	3,870	−15.9	6.6	3.2	41.10	14.93	This study
Beta - 572,543	T232-4	Sheep bone	3,540 ± 30	3,700–3,908	3,828	−17.1	5.6	3.2	41.94	15.28	This study
Beta - 572,542	T231-4	Pig bone	3,530 ± 30	3,700–3,894	3,791	−7.8	6.6	3.2	41.61	15.07	This study
Beta - 572,541	T102H8	Sheep bone	3,130 ± 30	3,247–3,445	3,355	−17.7	5.4	3.2	41.35	14.95	This study
Beta - 578,540	T249-2	Pig bone	2,990 ± 30	3,070–3,325	3,172	−7.1	6.4	3.2	41.03	15.14	This study
Beta - 563,895	ZKG60	Millet seed	3,540 ± 30	3,700–3,908	3,828	−10	—	—	—	—	This study
Beta - 563,896	ZKG105	Charcoal	3,540 ± 30	3,700–3,908	3,828	−25.8	—	—	—	—	This study
OZM232	ZGK4	Human bone	3,680 ± 40	3,896–4,147	4,019	−7.9	8.2	3.2	44	16	Atahan et al. (2014)
OZM221	ZKG Human 2	Human bone	3,500 ± 40	3,644–3,883	3,769	−8.4	9.7	3.2	44	16	Atahan et al. (2014)
OZQ354	ZKG1	Fruit shell	3,610 ± 35	3,832–4,076	3,918	—	—	—	—	—	Bao et al. (2018)
OZQ360	ZKG-S-29	Charcoal	3,560 ± 40	3,718–3,975	3,856	—	—	—	—	—	Bao et al. (2018)
OZQ355	MILLET ZKG2	Millet seeds	3,545 ± 35	3,700–3,964	3,835	—	—	—	—	—	Bao et al. (2018)
OZN201	SI1573	Bone	3,505 ± 30	3,692–3,870	3,771	—	—	—	—	—	Bao et al. (2018)
OZN202	SI1575	Bone	3,015 ± 30	3,077–3,339	3,211	—	—	—	—	—	Bao et al. (2018)
BK79053	IIIT23(5)	Charcoal	4,320 ± 90	4,620–5,285	4,921	—	—	—	—	—	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
BK80028	V(2)H5018	Charcoal	3,320 ± 70	3,390–3,811	3,547	—	—	—	—	—	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
WB84-76	I(3) H1071,1073	Charcoal	3,220 ± 70	3,251–3,626	3,438	—	—	—	—	—	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
WB84-77	I(3)H1055	Charcoal	3,190 ± 85	3,177–3,622	3,407	—	—	—	—	—	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
WB84-78	IIT228(4)	Charcoal	4,680 ± 80	5,072–5,591	5,411	—	—	—	—	—	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
WB84-79	I(4)H1058	Charcoal	3,420 ± 70	3,482–3,844	3,669	—	—	—	—	—	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)

Zone I (155–130 cm). The total numbers of phytoliths in zone I are 1,483. Elongate psilate type (37.8–45%) and Acicular hair cell type (40.1–50.6%) are the most common phytoliths. Common millet (1.2%) occurs in a single sample at the depth of 135 cm.

Zone II (130–60 cm). The total numbers of phytoliths in zone II are 5,571. Elongate psilate type (25.1–49.9%) remains the most common phytolith type, and there is a decrease in the Acicular hair cell type (9.6–38.7%). There are increases in the common millet (0–35.1%) and foxtail millet phytolith types (0–7.9%).

Zone III (60–0 cm). The total numbers of phytoliths in zone III are 2,734. The Elongate psilate type (25.3–41.3%) and Acicular hair cell type (24–27.8%) continue to decrease. Square (14.7–32.3%) and Rectangle (7.4–15.4%) increase substantially, and there is a slight increase in the Cuneiform bulliform type. However, the common millet and foxtail millet types disappear.

DISCUSSION

The Agro-Pastoral Economy at the ZKG Site

Phytoliths are tiny siliceous bodies precipitated in plant cells and deposited in the soil. They have distinct morphological characteristics due to differences in plant cell structure and soil type, and moisture and climatic conditions. As an important biological indicator, phytoliths have been widely used in research in palaeovegetation, palaeoecology and agricultural archaeology (Lv et al., 2009).

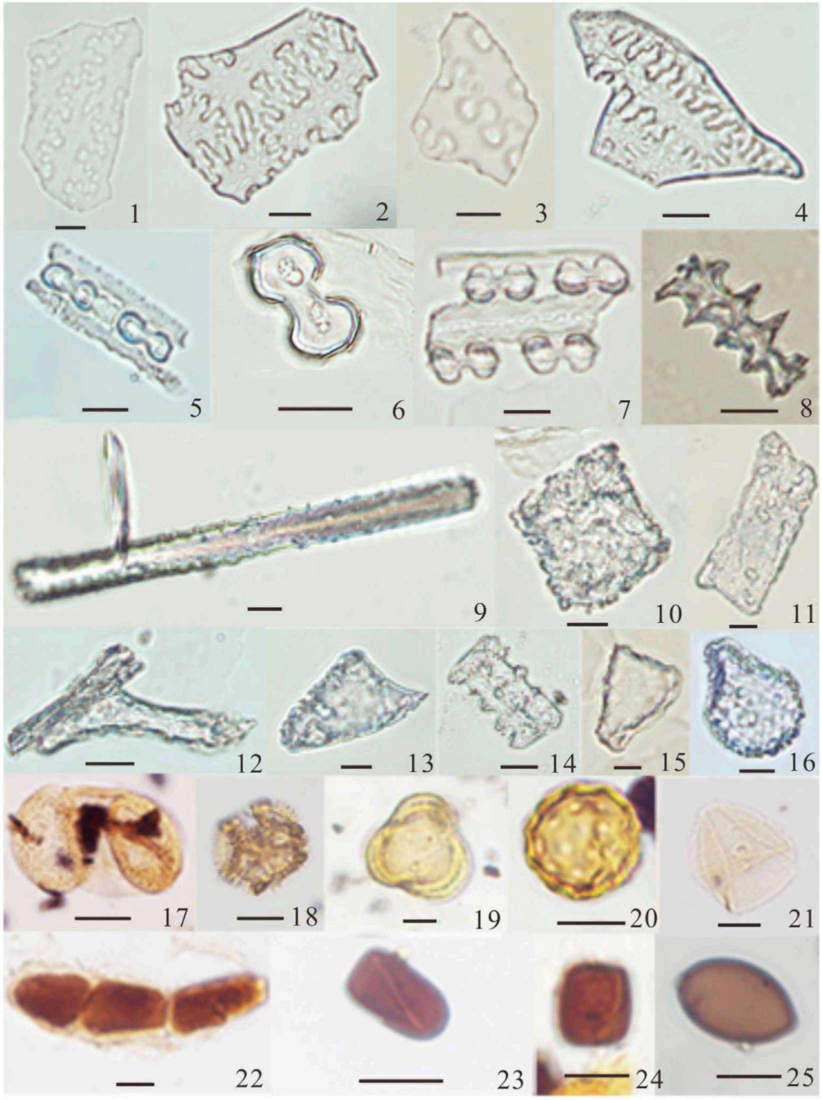

FIGURE 3 | Phytoliths, pollen and fungal spores from the ZKG section. 1, 2, 4, Broomcorn millet husk; 3, Foxtail millet husk; 5-7, Bilobate; 8, Elongate dendritic; 9, Elongate psilate; 10, Square; 11, Rectangle; 12, "Y" type; 13, Acicular hair cell; 14, Tooth type; 15, Fusiform; 16, Cuneiform bulliform; 17, Pinus; 18, Compositae-Taraxacumtype 19, Artemisia; 20, Chenopodiaceae; 21, Poaceae; 22–24, Sporormiella; 25, Sordaria (black lines indicate 10 μm).

The phytoliths of common millet and foxtail millet in the section are direct evidence of the cultivation of the parent plants at the site, and are consistent with the discovery of millet seeds and associated agricultural tools at the site (Institute of Cultural relics and Archaeology, Inner Mongolia Autonomous region, 2000; Bao et al., 2018). The AMS ^{14}C ages of two crop seeds from the ZKG site are 3,700 and 4,000 cal yr BP (median ages of 3,835 and 3,828 cal yr BP, respectively). There is a relatively high abundance of phytoliths in the sediments within this period, indicating that millet was cultivated in the vicinity of the site, and that there was a high intensity of planting activity (**Figure 6**). Phytoliths are absent from the sediments above 60 cm in the ZKG section, which may have been caused by a reduction in rainfed agriculture at the site.

The life cycle of fungal spores is closely related to the activity of herbivores. After breaking dormancy in the intestinal tract of animals, the spores are excreted and then propagate (Van Geel et al., 2011). Many studies have shown that fecal fungal spores can be used as indicators of domestic herbivores (Van Geel et al., 2003; Zhao et al., 2013; Huang et al., 2020, 2021). Therefore, the occurrence of fungal spores in the sediments of the ZKG site indicates the local presence of herbivorous domestic animals, which is consistent with the large quantity of domestic animal remains excavated from the site (Huang, 1996). The distribution of fungal spores in the strata is characterized by low percentages below the depth of 60 cm, indicating limited cattle and sheep rearing at that time, while the increased percentages above 60 cm indicate that animal husbandry increased (**Figure 6**).

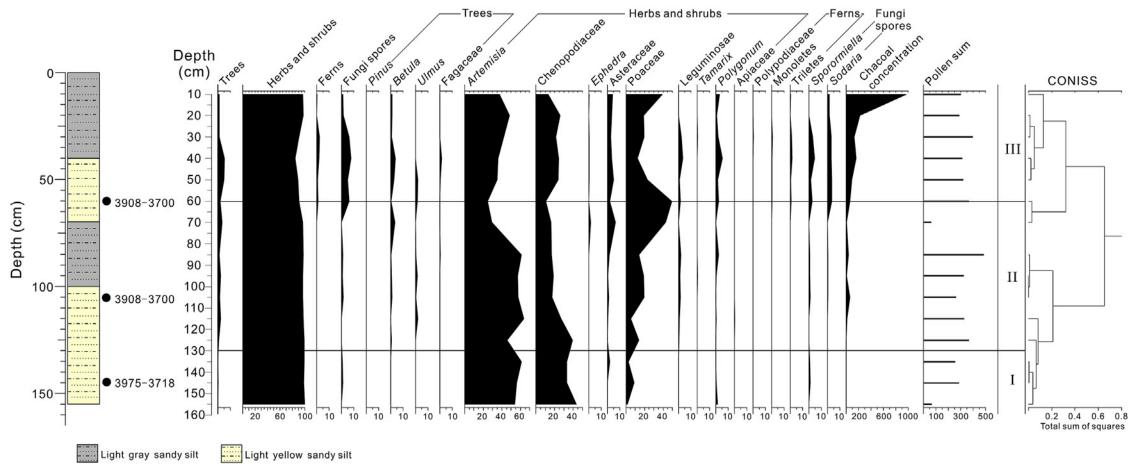

FIGURE 4 | Pollen percentage diagram for the ZKG section (only the major taxa are shown). The contents of fungal spores and charcoal particles are also shown.

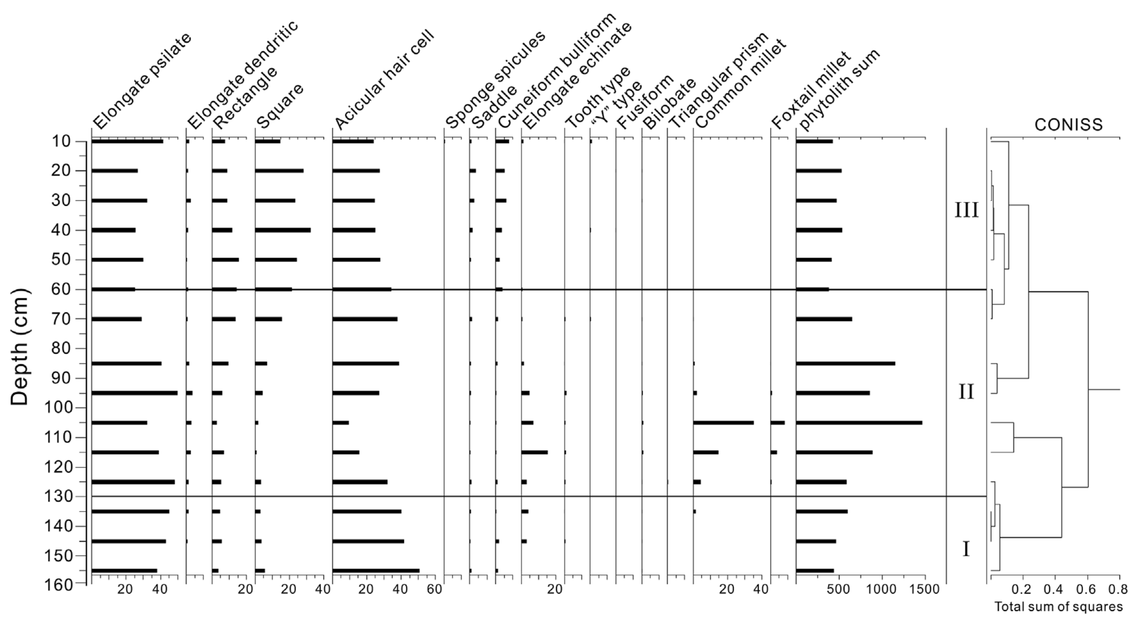

FIGURE 5 | Percentage diagram of the main phytolith types for the ZKG section.

The carbon isotope composition ($\delta^{13}C$) of the bones of domesticated pigs, cattle and sheep can reflect their diet and hence human feeding strategies (Hu S. M. et al., 2008; Chen et al., 2012). The $\delta^{13}C$ values of carbon isotopes of two pig bones from the ZKG site are −7.1‰ (3,791 cal yr BP) and −7.2‰ (3,172 cal yr BP), which indicates that their food was dominated by C_4 plant types. The $\delta^{13}C$ values of pigs are similar to those of human bones at the ZKG site (Atahan et al., 2014) (**Table 2**); moreover, the $\delta^{13}C$ values of the bones of humans and domestic pigs in North China are similar (Hu Y. W. et al., 2008). The $\delta^{13}C$ values of cattle and sheep indicate that C_3 plants were the dominant plant types consumed by these animals at the ZKG site. The $\delta^{13}C$ of cattle is also ~1‰ more positive than that of sheep, which may be related to the consumption of cultivated millet and millet byproducts. The Taosi site in the Central Plains is an important symbol of Chinese large urban centers (**Figure 1**; **Table 1**). The $\delta^{13}C$ values (average −11.25‰) of cattle bones at the Taosi site are indicative of a diet dominated C_4 plants, which may reflect the supply of fodder by humans (Chen et al., 2012). However, the $\delta^{13}C$ values of cattle bones at ZKG indicates that a lower proportion of C_4 plants was consumed than at the Taosi site.

The evidence provided by the contents of phytoliths and fungal spores of the section, combined with the archaeological evidence, reveals that a mixed agro-pastoral economy consisting of rainfed millet cultivation and animal husbandry (cattle and sheep) appeared at the ZKG site some 4,000 years ago. However,

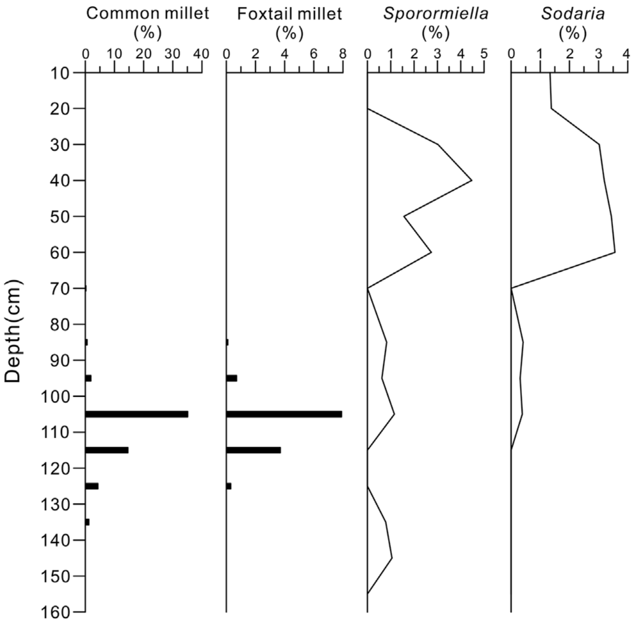

FIGURE 6 | Contents of common millet and foxtail millet phytoliths and fungal spores inthe ZKG section.

there were changes in the relative proportions of rainfed millet cultivation and pastoralism over time. Rainfed millet cultivation accounted for a high proportion of the agricultural activity in the early phase, but the proportion of pastoral activity increased subsequently. The nitrogen isotope composition ($\delta^{15}N$) of two human bones from ZKG were 8.2 and 9.7‰ (median ages of 4,019 cal yr BP and 3,769 cal yr BP, respectively). The 1.5‰ difference between the two indicates an increase of the nitrogen intake and hence an increase in animal husbandry (Atahan et al., 2014). Pig bones dating back 3,200 years have been found at the ZKG site, and pig rearing is direct evidence of settled agriculture. Although there may have been cultural or genetic exchanges with the Andronovo culture (Institute of Cultural relics and Archaeology, Inner Mongolia Autonomous region, 2000; Jeong et al., 2020; Wang et al., 2021), the area remained dominated by a settled agro-pastoral economy from the middle to the late Bronze Age (4,000–5,000 cal yr BP).

Agro-Pastoralism in the Steppe Region of Northern China

In the early mid-Holocene, human activity in the forest and steppe region of northern China mainly took the form of rainfed agriculture and pig rearing. For example, millet cultivation appeared at the Xinglonggou site in the West Liaohe River Basin between 8,000 and 7,500 cal yr BP (Zhao, 2005), and at the Dadiwan site, in the western part of the Loess Plateau, at 7,800–7,350 years cal yr BP (Liu et al., 2004). Pig rearing was also conducted at both sites. Agricultural tools have been excavated from Shihushan (6,700–6,000 cal yr BP), Wangmushan (5,300–4,900 cal yr BP), Xiyuan (5,000–4,800 cal yr BP) and Ashan (4,400–3,800 cal BP) in the northern Loess Plateau and in the Hetao area of the Ordos Plateau (Yang, 1997; Bao et al., 2018; Feng and Wei, 2018). We speculate that they are related to millet agriculture. But usewear and residue analyses on food processing stone tools from these sites have shown that plants including tubers are dominant (Liu et al., 2014; 2016). The seeds have been found from Xiaojiamao, Dakou, Zhaimao, Zhukaigou, Shimao sites (Bao et al., 2018). Millet, a C_4 plant, was an important food source for humans in the steppe region of northern China during 2,500–5,000 cal yr BP, then the ratio of C_3 plants in the diet began to increase after 2,500 cal yr BP (Atahan et al., 2014).

Evidence of cattle and sheep rearing gradually appeared in the region in the middle and late Holocene (from the time of the Longshan culture to the Bronze Age). For example, AMS ^{14}C ages of the remains of domestic cattle at Houtaomuga of 5,500–5,300 cal yr BP were obtained (Cai et al., 2018). AMS ^{14}C ages of 4,577–4,454 cal yr BP were obtained for cattle remains at the Ashan site, but it is unclear if they were domesticated (Bao et al., 2018). The latest AMS ^{14}C dating of cattle bone from the Hongliang site were 4,406–4,186 cal yr BP (Hu, 2021). The first directly cattle bones for the Hexi Corridor region, with the samples dating to 3,850–3,700 cal yr BP (Brunson et al., 2020). The earliest evidence of domestic sheep/goats in China may be at the Shizhaocun and Hetaozhuang sites in the western Loess Plateau; the estimated age range is 5,600–5,000 cal yr BP based on the archaeological context, but no direct AMS ^{14}C ages were reported (Yuan, 2010).

So far, published AMS ^{14}C ages for the remains of the earlist domesticated sheep/goats come from the Youyao (4,292–4,029 cal yr BP) site (Dodson et al., 2014). AMS ^{14}C ages of 4,406–4,151 cal yr BP were obtained for three sheep bones at the Jingbianmiaoliang site (Hu, 2021). An AMS ^{14}C age of 3,925 cal yr BP was obtained for sheep skin at Gumugou in Xinjiang (Wang, 1983). The dating results for mixed human and sheep bones from Xihe Lanqiao in Gansu Province are 3,450–2,877 cal yr BP (Chinese Archaeological Radiocarbon Collection, 1983). In addition, the AMS ^{14}C dating results for sheep/goat bones from Hexi Corridor are 4,413–3,073 cal yr BP (Yang et al., 2019). Other dates for sheep or cattle remains have been obtained for the sites of Shimao (4,300–3,800 cal yr BP), Muzhuzhuliang (~4,000 cal yr BP) and Zhengzemao (~4,800 cal yr BP) in Shaanxi Province; Yongxingdian in Zhunger Qi in Inner Mongolia Province (4,450–3,950 cal yr BP); Dakou (4,200–3,500 cal yr BP) and Taosi in Shanxi Province (~4,000 cal yr BP); and Yuanqu Shangcheng (3,300–2,800 cal yr BP), Tongtian cave (5,200–3,200 cal yr BP), Adunqiaolu (3,850–3,200 cal yr BP), Xiaohe (4,000 cal yr BP) and Shirenzigou (2,300 cal yr BP) in Xinjiang. However, no direct AMS ^{14}C dating has been reported (**Figure 6**) (Wei, 2000; Cong et al., 2013; You et al., 2014; Yu et al., 2018).

Opposite to the eastern end of the Eurasian steppe (including the steppe region of northern China), the Yamnaya culture (5,300–4,200 cal BP) originated in the western part of the Eurasian steppe and practiced an economy based on hunting and grazing. The Yamnaya people spread eastward and reached Lake Baikal, which

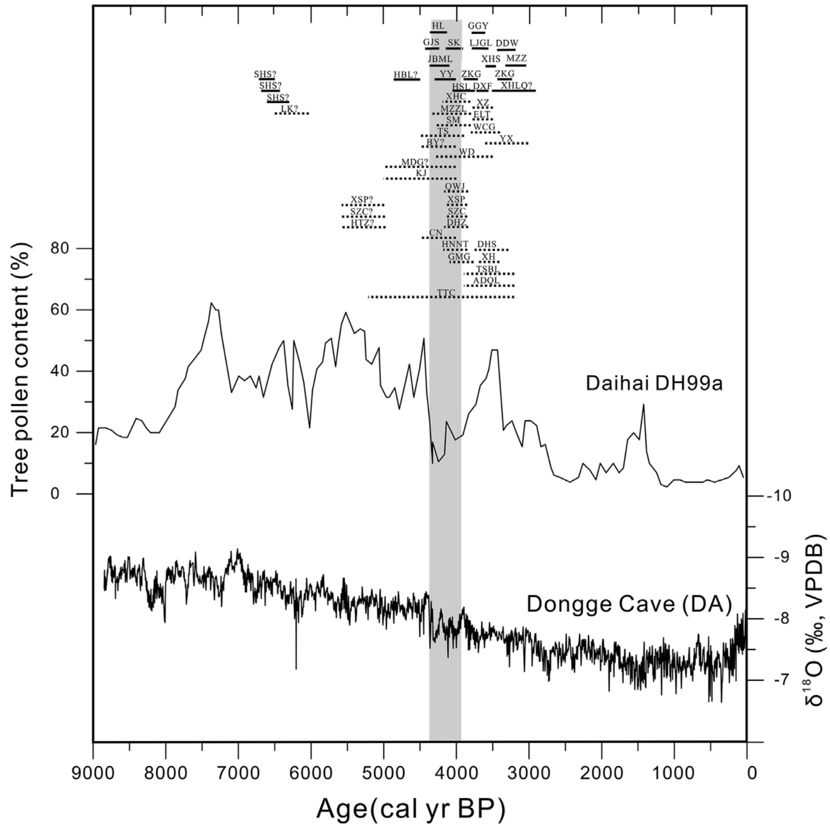

FIGURE 7 | Ages of the remains of domestic sheep at sites in North China (solid line indicates AMS 14C ages, dashed line indicates age inferred from the cultural context, and "?" indicates that it is uncertain whether the sheep were domesticated). Also shown are tree pollen percentages from Daihai (Xiao et al., 2004) and the oxygen isotope record from Dongge cave (Wang et al., 2017). The grey shading represents drought events at ~4,200 cal yr BP. The full names of the sites are shown in **Table 1**.

was the eastern limit of their extension (Zhou et al., 2020; Wang et al., 2021; Narasimhan, et al., 2019). The Afanasyevo culture (5,000–3,500 cal yr BP), which was believed to have been formed by the eastward spread of the Yamnaya culture (Cong and Jia, 2020; Honeychurch et al., 2021). And the Afanasyevo culture which appeared in the central Eurasian steppe, was characterized by sheep/goat and cattle rearing (Honeychurch et al., 2021). During the middle and late Bronze Age, the Andronovo culture (1900–1,500 cal yr BP) developed in the central Eurasian steppe. Several studies have proposed that practiced a sedentary from of animal grazing, and raised animals such as horses, sheep/goat and cattle (Kuzmina, 2008).

According to recent ancient DNA research, during the early Bronze Age there was a possible cultural connection between the populations of Yamnaya and the Eastern Eurasian steppe (Wang et al., 2021). The economy of the steppe of northern China at this time was dominated by rainfed agriculture and pig rearing. Cattle and sheep/goat were also raised sporadically, but did not play the dominant role. By the middle to late Bronze Age, cattle and sheep/goat rearing had increased substantially, similar to the subsistence economy of the Andronovo culture, but horse raising was uncommon. According to this study, the mixed economy of rainfed agriculture and cattle and sheep/goat rearing in the steppe region of northern China was practiced as early as 4,000 years ago. In addition to cultural influences from the central and western steppe areas, climatic and environmental changes were an important factor that must be considered when interpreting patterns of subsistence activity, which is discussed below.

Climatic Influence on the Mixture of Pastoralism and Millet Cultivation in the Steppe Region of Northern China

The steppe region of northern China, dominated by arid and semiarid ecosystems, is located on the margin of the zone of influence of the Asian summer monsoon. A shift in the East Asian monsoon occurred some 4,000 years ago and it had an important impact on the environment of East Asia. Stalagmite records from Dongge Cave show that the intensity of the Asian summer monsoon weakened from 4,400 years BP to 3,900 years BP corresponding to a decrease in North Atlantic sea surface temperatures (Bond et al., 1997; Demenocal et al., 2000; Wang, 2017) (**Figure 7**). Pollen records and quantitative palaeoclimatic reconstructions from Gonghai in Taihang Mountain and

Tianchi in Liupan Mountain indicate a substantial decrease in precipitation in the monsoon margin zone at ~4,000 years BP (Zhang et al., 2010; Chen, 2015; Li et al., 2017). Additionally, the pollen percentages of Chenopodiaceae increased significantly during 4,400–3,350 cal yr BP at Hulun Lake, indicating arid climatic conditions (Wen et al., 2010).

According to a comprehensive study of environmental and archaeological records (Cui et al., 2019; Sun et al., 2019), the decline of major Neolithic cultures in China was closely related to the weakening of the monsoon some 4,000 years ago. Neolithic cultures, such as the Qijia, Laohushan, Hongshan, Longshan and Liangzhu, all declined and ended in or after this period (Wu and Liu, 2001; Mo et al., 2003; An et al., 2005; Yang et al., 2015).

Major drought events at ~4,000 cal yr BP and their impacts may have been of global extent. The drought event during 4,200–3,900 years BP caused the abrupt decline of the Akkadian empire in Mesopotamia; and large urban centers in Egypt, on the Nile, and in India, on the Indus, also declined at the same time. Moreover, large urban centers in Anatolia, Aegean and Levant also developed during the Bronze Age (Weiss et al., 1993; Weiss and Bradley, 2001). The occurrence of severe droughts is suggested to have been a major cause of the declines of these large urban centers, on the one hand, and on the rise of a nomadic culture in steppe regions (Weiss and Bradley, 2001).

Tree pollen percentages in the Daihai DH99 drill core decreased substantially during 4,450–3,950 cal yr BP, while herb pollen types increased, indicating a pronounced cold and dry interval in the marginal area of the summer monsoon zone (Xiao et al., 2004) (**Figure 7**). The pollen record from the Zhukaigou site also suggests typical steppe vegetation, dominated by *Artemisia* and Chenopodiaceae, that would have favored the development of cattle and sheep rearing. Sheep/goats and cattle may have appeared in northern China some 5,000 years ago, but they were not universally raised. The period after the 4,200 years BP drought event, with substantially decreased precipitation and the expansion of steppe vegetation, coincided with a substantial increase in the numbers of domestic cattle and sheep (**Figure 7**). The low crop yields during this arid period may have been insufficient to support the population, while on the other hand the steppe vegetation benefited a pastoral economy. It is evident that the inhabitants of the region were able to adapt to these major environmental changes and adopt a modified economic structure which enabled the population carrying capacity of the land to be maintained. Therefore, we suggest that the combination of rainfed agriculture and pastoralism increased the adaptability of the inhabitants of northern China to arid conditions and increased their socioeconomic resilience.

CONCLUSION

A combined analysis of fungal spores, pollen and phytoliths of a sedimentary section at the Bronze Age ZKG archaeological site, combined with the results of AMS ^{14}C dating of domestic animal remains, reveals that the inhabitants of the site relied on millet cultivation and pastoralism. The intensity of pastoralism increased from the early to the late stage at the site. The mixture of pastoralism and millet cultivation was common in the steppe region of northern China after ~4,000 cal yr BP. The 4,200 years BP climatic event was likely an important factor responsible for the development of a mixed agro-pastoral economy in the region.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study in accordance with the local legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

YaZ and KZ did the research and wrote the article. YiZ identified the animal materials. SH and XZ participated in the research and offered suggestions for the article. LL participated in the identification of phytoliths experiment. JL participated in stable isotope experiment. XL guided the experiment and offered suggestions for the article.

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REVIEW
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Animals for Tools: The Origin and Development of Bone Technologies in China

Shuwen Ma[1†] *and Luc Doyon*[1,2*†]

[1]*Institute of Cultural Heritage, Shandong University, Qingdao, China,* [2]*Université de Bordeaux, Centre National de la Recherche Scientifique UMR5199 – PACEA, Pessac, France*

The origin and development of bone technologies in China are reviewed in the light of recent discoveries and compared to trends emerging from the European and African archaeological records. Three categories of osseous tools are targeted: 1) unmodified bone fragments bearing traces of use in technological activities; 2) bone fragments modified to a variable extent with techniques generally used in stone technologies; 3) osseous fragments entirely shaped with techniques fit for the manufacture of formal bone tools. Early evidence of bone technologies in China are sporadically found in contexts dated between 1.8 and 1.0 Ma. By the late MIS6–early MIS5, bone tools are well-integrated in the technological systems of Pleistocene populations and the rules guiding their use appear increasingly standardized. In addition, the first evidence for the use of osseous material in symbolic activities emerges in the archaeological record during this period. Finally, between 40 and 35 ka, new manufacturing techniques and products are introduced in Late Palaeolithic technological systems. It is first apparent in the manufacture of personal ornaments, and followed by the production and diversification of formal bone tools. By that time, population dynamics seem to become materialized in these items of material culture. Despite regional specificities, the cultural trajectories identified for the evolution of bone technologies in China seem entirely comparable to those observed in other regions of the world.

Keywords: Pleistocene, bone tools, cultural evolution, symbolism, archaic humans, *Homo sapiens*

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Dongju Zhang, Lanzhou University, China

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Justin Bradfield, University of Johannesburg, South Africa
Yanhua Song, Shanxi University, China

****Correspondence:***
Luc Doyon
luc.doyon@umontreal.ca

†ORCID:
Ma Shuwen, orcid.org/0000-0001-5710-153X;
Luc Doyon, orcid.org/0000-0001-7163-6186

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1 INTRODUCTION

The evolution of bone technologies represents a key issue in paleoanthropological research. First, from a subsistence perspective, the origin of bone tools signals a major shift in the way past populations perceived the animal species at their disposal, specifically when faunal resources' utility expanded from their primary uses, i.e., meat consumption, hide processing, fat use, and fuel, to include the manufacture and use of cultural items made of hard animal tissues. Second, from a social perspective, bone tools represent an ideal proxy to investigate social dynamics. Indeed, owing to their mechanical properties, prehistoric populations could impose a form to the object by applying a sequence of adapted techniques, e.g., scraping, incision, grinding, gouging, etc. When studying implements produced with these techniques, archaeologists can document variation in how knowledge was implemented for the manufacture of various tool types, differentiate between the form and function of an object, and explore topics such as technological organization, pattern of cultural transmission, population dynamics, etc.

Expanding on Klein (2009) definitions, it is possible to distinguish three main categories of bone tools. The first category includes unmodified osseous fragments bearing clear evidence of their use. The second comprises fragments intentionally modified albeit with techniques usually devoted to the manufacture of stone tools. The third refers to osseous fragments entirely shaped with techniques fit to transform hard animal tissues. The first two categories are usually referred to as "expedient tools" while the third is known as "formal tools" (Klein, 2009). Here, the aim is to provide a synthesis on the tipping points that punctuated the origin and development of these broad artefactual categories and compare recent evidence from China to the African and European archaeological record. This review highlights that, despite some regional specificities, the cultural trajectories identified for the evolution of bone technologies in China are largely comparable to those observed in other regions of the world.

2 PLEISTOCENE OSSEOUS TECHNOLOGY IN AFRICA AND EUROPE

Four tipping points can be identified in the origin and development of bone technologies in Africa and Europe. The first tipping point occurs between 2.0 and 1.5 Ma, a period at which the first occurrences of the use of bone appear simultaneously in the South and East African archaeological records. In South Africa, a number of sites attests to the use of mostly unmodified bone fragments as digging implements by *Australopithecus robustus* (Brain and Shipman, 1993; Backwell and d'Errico, 2001; Backwell and d'Errico, 2008; d'Errico and Backwell, 2003; Val and Stratford, 2015; Stammers et al., 2018; Hanon et al., 2021). Meanwhile, in East Africa, occupation layers at Olduvai Bed I and II yielded numerous bone fragments bearing evidence of intentional shaping. Technological and use-wear studies suggest that early members of our genus, *Homo*, used these implements for hide-working, butchery, digging, stone knapping and, possibly, hunting activities (Backwell and d'Errico, 2004; Pante et al., 2020). It remains unclear why organic technologies were integrated in the technological systems of our ancestors. However, it appears reasonable to believe that activities attested since at least 2.6 Ma, such as stone knapping (Harmand et al., 2015; Lewis and Harmand, 2016), marrow extraction (Domínguez-Rodrigo et al., 2005), and wood working (Lemorini et al., 2014, 2019), may have allowed early hominins to recognize the technological potential of osseous materials and equipped them with the skills required to modify and utilize bone flakes.

Between 1.5 Ma and the second half of the Middle Pleistocene, the archaeological record yielded only a handful of evidence for the use or modification of osseous remains for technological purpose. Most often, these items correspond to bone retourchers, i.e., bone fragments used in stone knapping activities (Goren-Inbar, 2011; Smith, 2013; Moigne et al., 2016), or bifaces made on *Elephantidae* long bone fragments (Kretzoi and Dobosi, 1990; Mania and Mania, 2003; Rabinovich et al., 2012; Sano et al., 2020). In rare occasion, hard animal remains bearing incised patterns (Mania and Mania, 1988; Sirakov et al., 2010; Joordens et al., 2015) are interpreted as early experimentations with this raw material either to permanently record information or to express some form of symbolic behaviors. Collectively, these occurrences, albeit scattered in both time and space, suggest that the use osseous materials for technological purposes was never completely abandoned by prehistoric populations during this period.

The second tipping point occurs mainly in Europe at the onset of the Marine Isotope Stage (MIS) 9. Between ~350 and 300 ka, bone bifaces and retouchers become commonplace (Naldini et al., 2009; Anzidei et al., 2012; Moncel et al., 2012; Blasco et al., 2013; Daujeard et al., 2014; Boschian and Saccà, 2015; Santucci et al., 2016; Villa et al., 2021). Furthermore, the archaeological record attests to a noticeable increase in the diversity of expedient bone tool morphology and of the use-wear development on them, possibly reflecting an expansion in the behavioral spectrum for which they were used (Rosell et al., 2011; Julien et al., 2015; Di Buduo et al., 2020; Bonhof and van Kolfschoten, 2021). From the MIS9 onward, the use of expedient tools becomes a lasting aspect of Pleistocene technological systems alongside the multiple innovations that define the third and fourth tipping points (e.g., Daujeard, 2007; Burke and d'Errico, 2008; Verna and d'Errico, 2011; Mallye et al., 2012; Tartar, 2012; Abrams et al., 2014; Daujeard et al., 2018; Yeshurun et al., 2018; Baumann et al., 2020; Hallett et al., 2021).

The third tipping point is restricted to the African continent. Between 90 and 65 ka, a number of formal bone tools appear in the archaeological record. The distribution of each type presents a marked pattern of regionalization with bone knives and smoothers found in Northeast Africa (Bouzouggar et al., 2018; Hallett et al., 2021), barbed points in Central Africa (Yellen, 1998), and awls, wedges and hunting implements in South Africa (Henshilwood et al., 2001; d'Errico and Henshilwood, 2007; d'Errico et al., 2012a; Bradfield et al., 2020). In Africa, the emergence of formal bone tools is broadly contemporaneous with the appearance of personal ornaments (d'Errico et al., 2005; d'Errico et al., 2008; d'Errico et al., 2009; Vanhaeren et al., 2006, 2019; Bouzouggar et al., 2007; Bar-Yosef Mayer et al., 2009; Val et al., 2020), although recent discoveries from Bizmoune Cave, Morocco, indicates personal ornaments may have been manufactured up to 50 millennia prior to the first bone tools in this particular region (Sehasseh et al., 2021). Interestingly, both personal ornaments and formal bone tools disappear from the African archaeological record *c.* 60 ka. This apparent hiatus in material culture lasts for roughly 15 millennia.

Contrary to the aforementioned, the fourth tipping point is not restricted to a particular region and/or continent; it is indeed a global phenomenon. From 45 ka, formal bone tools and personal ornaments make a lasting reappearance in the archaeological record, this time in multiple regions of the Old World. Evidence from Europe (d'Errico et al., 2003; Zilhão et al., 2010; Caron et al., 2011; d'Errico et al., 2012c; Soressi et al., 2013; Julien et al., 2019; Sano et al., 2019; Arrighi et al., 2020; Velliky et al., 2021), the Levant (Kuhn et al., 2001; Tejero et al., 2016; Tejero et al., 2018; Bar-Yosef Mayer, 2020; Tejero et al., 2020), East and South Africa (d'Errico et al., 2012b; d'Errico et al., 2020),

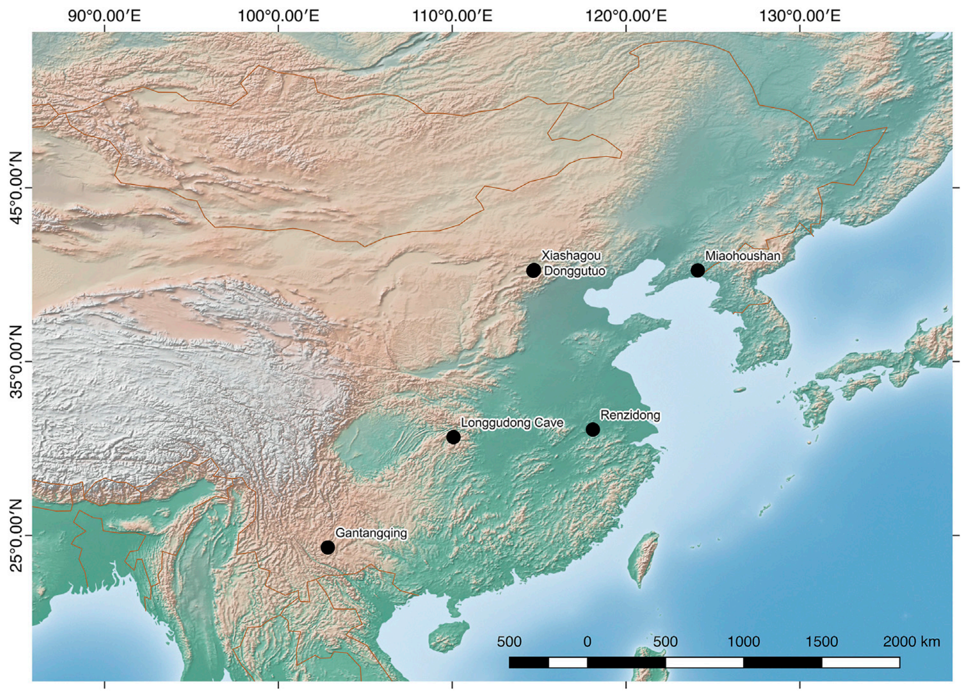

FIGURE 1 | Distribution of Chinese Lower Paleolithic sites where osseous technology was reported in the literature (see **Table 1** for details). Map made by LD using QGIS v. 2.14.3-Essen (Free Software Foundation, Inc., Boston) and free vector and raster from Natural Earth (naturalearthdata.com).

South and Central Asia (Golovanova et al., 2010; Perera et al., 2016; Krivoshapkin et al., 2018; Shalagina et al., 2018; Belousova et al., 2020; Langley et al., 2020; Shunkov et al., 2020) as well as the Asian Pacific Island and Australia (O'Connor et al., 2014; Langley et al., 2016b; Langley et al., 2016a; Langley et al., 2019; Langley et al., 2021) attests to the penecontemporaneous development of a variety of formal bone tool types, the diversification of the manufacturing processes and techniques, the convergent innovation in the production of hunting armatures and the noticeable expansion in the variety of symbolic material culture items.

3 PLEISTOCENE BONE TECHNOLOGY IN CHINA

In light of the trends identified above, one may wonder to what extent the Chinese archaeological record is comparable to the rest of the Old World when it comes to the origin and development of osseous technologies. This question is even more pertinent when we consider the central place occupied by this region in paleoanthropological studies, especially with regard to Pleistocene hominin dispersal events and complex population dynamics (Wu, 2004; Shang et al., 2007; Hou and Zhao, 2010; Keates, 2010; Liu et al., 2010; Kaifu and Fujita, 2012; Fu et al., 2013; Shen et al., 2013; Bae et al., 2014; Liu et al., 2015; Zhu et al., 2015; Bae et al., 2017; Cai et al., 2017; Kaifu, 2017; Li et al., 2017; Martinón-Torres et al., 2017; Yang et al., 2017; Bae et al., 2018; Chen et al., 2019; Dennell et al., 2020; Massilani et al., 2020; Zhang et al., 2020; Curnoe et al., 2021; Higham and Douka, 2021; Martinón-Torres et al., 2021; Mao et al., 2021; Sun et al., 2021). In what follows, three tipping points are identified.

Much like the rest of the Old World, the first tipping point relates to the first occurrences of osseous technology in the archaeological record. A number of sites suggests a very ancient origin for the intentional modification of bones for technological purposes (**Figure 1**; **Table 1**). Between 1.8 and 1.0 Ma, key sites include Longgudong Cave, Renzidong, and Donggutuo (Wei, 1985; Zhang et al., 2000; Zhu et al., 2003; Li, 2004; Hou and Zhao, 2010). In all these cases, the reported tools consist of osseous fragments modified by direct percussion, i.e., in a fashion similar to stone knapping. From 1.0 Ma and throughout the Late Paleolithic, reports of similar technology are often reported in the literature (**Figures 2**, **3**; **Table 1**), although some evidence would perhaps benefit from a reassessment using modern analytical methods to ensure the anthropogenic nature of the modification. Thus far, however, previous reviews have highlighted a subtle change over time when it comes to the modification of osseous remains through direct percussion (An, 2001; Feng, 2004; Wei G. et al., 2017). For most of the Early Paleolithic, the tools are generally crude and simple, and the flakes are mainly removed from the distal end of bone fragments to produce pointed implements. From the Middle and throughout the Late Paleolithic, direct percussion is used to shape the long edges of osseous fragments by a series of successive blows. In some cases, overlapping flake removal scars appear to indicate these long cutting edges were at times reshaped, perhaps to increase the longevity of the tools for whatever tasks they were considered fit (Feng, 2004).

TABLE 1 | Summary of occurrence of Pleistocene osseous technology in China.

Site	County	Province	Cultural attribution	Tool types			References
				Unmodified bone fragments with traces of use	Bone fragments modified by direct percussion	Formal bone tools	
Donggutuo	Yangyuan	Hebei	Lower Paleolithic		X		Wei (1985), Zhu et al. (2003)
Gantangqing	Jiangchuan	Sichuan	Lower Paleolithic	X	X		Zhang et al. (1989), Yunnan Institute of Cultural Relics and Archaeology and Liu (2016)
Longgudong Cave	Jianshi	Hubei	Lower Paleolithic		X		Hou and Zhao (2010)
Miaohoushan	Benxi	Liaoning	Lower Paleolithic		X		Liaoning Provincial Museum and Benxi Municipal Museum (1986)
Renzidong	Fanchang	Anhui	Lower Paleolithic		X		Zhang et al. (2000), Hou and Zhao (2010)
Xiashagou	Yangyuan	Hebei	Lower Paleolithic	X	X		Wang et al. (1988)
Bashiyi Quarry	Jiulongpo	Chongqing	Middle Paleolithic		X		Wei et al. (2017b)
Dadong	Panxian	Guizhou	Middle Paleolithic		X		Miller-Antonio et al. (2000)
Dingcun	Xiangfen	Shanxi	Middle Paleolithic	X	X		Tao and Wang (1987)
Jiangjiawan	Qingyang	Gansu	Middle Paleolithic		X		Xie and Zhang (1977)
Jujiayuan	Qingyang	Gansu	Middle Paleolithic	X	X		Xie and Zhang (1977)
Lingjing	Xuchang	Henan	Middle Paleolithic	X	X		Li and Shen (2010), Li and Shen (2011), Doyon et al. (2018), Doyon et al. (2019), Doyon et al. (2021)
Longtandong	Hexian	Anhui	Middle Paleolithic	X	X		Lu (1990)
Longtanshan Cave 1	Chenggong	Yunnan	Middle Paleolithic		X		Hu (1977)
Loufangzi	Qingyang	Gansu	Middle Paleolithic		X		Xie and Zhang (1977)
Nanliang	Houma	Shanxi	Middle Paleolithic		X		Hu (1961)
Wulanmulun	Ordos (City)	Inner Mongolia	Middle Paleolithic		X		Hou et al. (2012), Zhang L.-m. et al. (2016)
Xujiayao	Yanggao	Shanxi	Middle Paleolithic	X	X		Jia et al. (1979)
Zhaocun	Qian'an	Hebei	Middle Paleolithic		x		Zhang (1989)
Zhijidong	Wangzongdain	Henan	Middle Paleolithic		X		Zhang and Liu (2003)
Zhoujiayoufang	Yushu	Jilin	Middle Paleolithic		X		Sun et al. (1981)
Zhoukoudian Loc. 1	Beijing	Beijing	Middle Paleolithic		X		Jia (1959), Jia (1989)
Jinniushan	Yingkou	Liaoning	Middle and Upper Paleolithic		X	X	Jinniushan Joint Excavation Team (1978)
Yumidong	Wushan	Chongqing	Middle and Upper Paleolithic		X		He (2019)
Bailiandong	Liuzhou	Guangxi	Upper Paleolithic			X	Lotus Cave Science Museum et al. (1987)
Baiyanjiaodong	Puding	Guizhou	Upper Paleolithic		X	X	Cai (2012)
Beiyaowan	Heshun	Shanxi	Upper Paleolithic		X		Wu and Chen (1989)

(Continued on following page)

TABLE 1 | (*Continued*) Summary of occurrence of Pleistocene osseous technology in China.

Site	County	Province	Cultural attribution	Tool types			References
				Unmodified bone fragments with traces of use	Bone fragments modified by direct percussion	Formal bone tools	
Chuandong	Puding	Guizhou	Upper Paleolithic		X	X	Mao and Cao (2012), He (2019)
Chuanfandong	Sanming	Fujian	Upper Paleolithic			X	Chen et al. (2001)
Dahe	Fuyuan	Yunnan	Upper Paleolithic		X	X	Ji (2008)
Daxingtun	Angangxi	Heilongjiang	Upper Paleolithic		X		Gao (1988)
Dushizai	Yangjiang	Guangdong	Upper Paleolithic			X	Zhou (1994)
Gezishan Loc. 10	Wuzhong	Ningxia Hui Autonomous Region	Upper Paleolithic			X	Zhang S. et al. (2019)
Gulongshan	Wafangdian	Liaoning	Upper Paleolithic	X	x		Zhou et al. (1990)
Laolongdong	Yuxi	Yunnan	Upper Paleolithic			x	Bai, (1998)
Liyuzui	Liuzhou	Guangxi	Upper Paleolithic			X	Zhou (1994)
Longquandong	Luanchuan	Henan	Upper Paleolithic			X	School of History Beijing Normal University et al. (2017)
Ma'anshan	Tongzi	Guizhou	Upper Paleolithic			X	Zhang S. et al., 2016
Ma'anshan	Yangyuan	Hebei	Upper Paleolithic			X	Xie et al. (2006)
Maomaodong	Yixing	Guizhou	Upper Paleolithic	X		X	Cao (1982)
Shiyu	Shuozhou	Shanxi	Upper Paleolithic		x		Zhang (1991)
Shizitan Loc. 29	Shizihe	Shanxi	Upper Paleolithic			X	Song et al. (2016), Song et al. (2019), d'Errico et al. (2018)
Shuidonggou Loc. 1	Binhe	Ningxia Hui Autonomous Region	Upper Paleolithic			X	Jia et al. (1964)
Shuidonggou Loc. 2	Binhe	Ningxia Hui Autonomous Region	Upper Paleolithic		X		Madsen et al. (2001)
Shuidonggou Loc. 12	Binhe	Ningxia Hui Autonomous Region	Upper Paleolithic			X	Zhang Y. et al. (2016), Zhang Y. et al. (2019), d'Errico et al. (2018), Zhang et al. (2018)
Wangfujing	Beijing	Beijing	Upper Paleolithic	X	X		Li et al. (2000)
Xianrendong	Shoushan	Jilin	Upper Paleolithic		X		Chen and Li (1994)
Xiaogushan	Haicheng	Liaoning	Upper Paleolithic			X	Huang et al. (1986)
Xuetian	Wuchang	Heilongjiang	Upper Paleolithic		X		Yu (1988)
Yancoudong	Guiyang	Hunan	Upper Paleolithic			X	Zhang (1965), Li (1982)
Yanjiagang	Harbin (City)	Heilongjiang	Upper Paleolithic		X		Heilongjiang Provincial Cultural Relics Management Committee et al. (1987)
Yuchanyan	Daoxian	Hunan	Upper Paleolithic			X	Yuan (2002)
Zhoukoudian Upper Cave	Beijing	Beijing	Upper Paleolithic	X	X	X	Pei (1939), d'Errico et al. (2018), d'Errico et al. (2021)
Ziyangren	Ziyang	Sichuan	Upper Paleolithic			X	Zhang (1965)

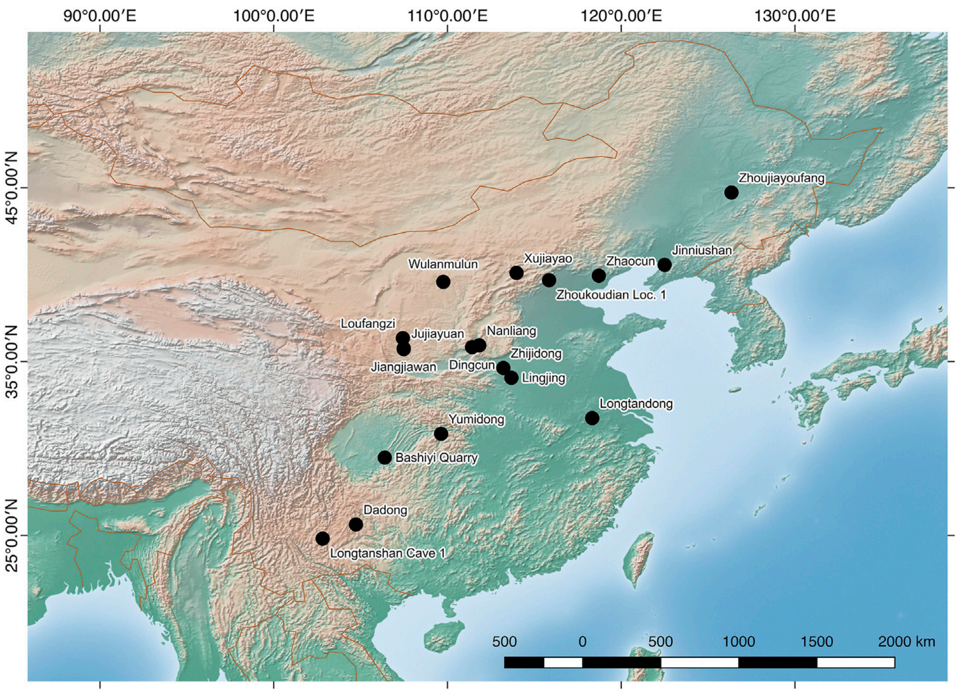

FIGURE 2 | Distribution of Chinese Middle Paleolithic sites where osseous technology was reported in the literature (see **Table 1** for details). Map made by LD using QGIS v. 2.14.3-Essen (Free Software Foundation, Inc., Boston) and free vector and raster from Natural Earth (naturalearthdata.com).

In contrast to what is observed in Europe during the MIS9, one may wonder whether any hint exists in favor of a functional diversification of the expedient bone tools in China during the Middle Pleistocene. The case of Lingjing, layer 11, an early Late Pleistocene kill/butchery site dated between 125 and 105 ka, provides a peculiar outlook on this issue. This occupation layer has yielded a rich and well-preserved faunal assemblage as well as important hominin remains (Li et al., 2017). Recent research conducted by zooarchaeologists, taphonomists and technologists allowed the identification of dozens of bone tools and revealed an unsuspected behavioral complexity. The microscopic observation of bone surface modifications permitted the recognition of antler soft hammers, i.e., tools used to remove flakes from a block during stone knapping (Doyon et al., 2018); bone retouchers as well as passive and active pressure flakers made of bone and antler, i.e., three tool types used to shape and retouch the cutting edges of stone implements but used in distinct motions (Doyon et al., 2019); and, equid and bovid metapodials used in long bone fracturing activities to access the marrow (van Kolfschoten et al., 2020; Bonhof and van Kolfschoten, 2021). Furthermore, two large mammal rib bone fragments bearing a pattern consisting of sequential linear incisions–one of them preserves remnants of ochre residues between and within the lines on its surface–suggest the visitors at the site may have intended to permanently record information on these remains or express some form of symbolic behaviors while producing the patterns (Li et al., 2019). During the 2005–2018 excavations of layer 11, some osseous fragments were isolated owing to the multiple flake removal scars they bear and, in some cases, the presence of an unusual polish (Li and Shen, 2010, 2011; Doyon et al., 2021). Experimentation in fracturing horse long bones for marrow extraction evidenced this activity could not account for the number and relative position of the flake removal scars observed on many archaeological specimens. It was therefore suggested that a sub-sample of 56 items were deliberately modified and could be interpreted as expedient bone tools (Doyon et al., 2021). Finally, morphometric comparison of these tools yielded surprising results. Among bone retouchers, the Lingjing visitors appear to have selected cervid metapodials to use them over long periods of time. These specimens present a high degree of standardization compared to the other large mammal long bone fragments used as retouchers and found at the site. This morphometric standardization was achieved by the marginal shaping through direct percussion, which likely increase the tool's prehensility and ergonomic (Doyon et al., 2018). Likewise, when comparing the dimension of the stone tools and the bone fragments with flake removal scars interpreted as expedient tools, a morphometric continuum is demonstrated, which appears to indicate a functional complementarity between the two aspects of material culture. Given the site function, it was hypothesized these bone tools may have been used in butchery and carcass processing activities (Doyon et al., 2021). Collectively, the results from Lingjing suggest we are in presence of a long-lasting tradition. The breath of activities in which bone implements are used, the evident selection in raw material for tools devoted to specific activities or receiving particular care, and the morphometric complementarity between lithic and bone

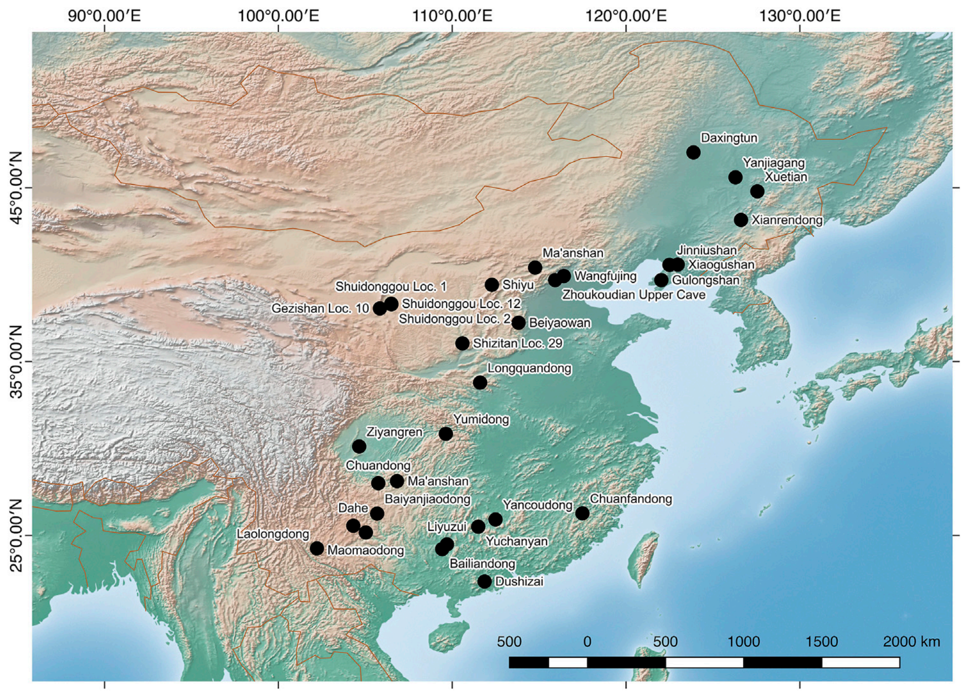

FIGURE 3 | Distribution of Chinese Upper Paleolithic sites where osseous technology was reported in the literature (see **Table 1** for details). Map made by LD using QGIS v. 2.14.3-Essen (Free Software Foundation, Inc., Boston) and free vector and raster from Natural Earth (naturalearthdata.com).

tools are all indicators suggesting that a functional diversification in osseous technologies was well-established by the end of MIS6 and the onset of MIS5. In this sense, Lingjing represents, in and of itself, a second tipping point in the evolution of Chinese Pleistocene bone technology. Future research on the origin of this cultural adaptive system may very likely push back the timing of this functional diversification, and perhaps make it comparable to what is observed in Europe.

The third tipping point occurs between 40 and 35 ka. As it was the case in the rest of the Old World, this period testifies to the emergence of formal bone tools both in North and South China (**Figure 3**; **Table 1**). These two regions attest to a convergent evolution in hunting implements. Indeed, the barbed and projectile armatures from Xiaogushan in the North (Huang et al., 1986; Zhang et al., 2010) are broadly contemporaneous with the barbed implements from Ma'anshan in the South (Zhang L.-m. et al., 2016). Throughout the Late Paleolithic, a diversification in formal bone tool types is apparent in the Chinese archaeological record (e.g., Qu et al., 2013; Zhang S. et al., 2016; Zhang et al., 2018; d'Errico et al., 2018; Wang et al., 2020). Furthermore, manufacturing techniques befitted for the transformation of osseous materials are being developed. Some techniques, such as scraping, incising, gouging, or grooving, are identical to those developed in the rest of the Old World. Others, however, appear to be more regionally circumscribed. This is the case for grinding, an ubiquitous technique used in formal bone tool manufacture in Asia during the Late Paleolithic (Rabett and Piper, 2012; O'Connor et al., 2014; Aplin et al., 2016; Zhang Y. et al., 2016; Perera et al., 2016; Li et al., 2020), yet, seldom observed in European Upper Paleolithic (Camps-Faber, 1976; d'Errico et al., 2012c; Goutas, 2013; Langley, 2016) or in African Middle Stone Age contexts (d'Errico and Henshilwood, 2007; Backwell and d'Errico, 2016; Vanhaeren et al., 2019). Outside Asia, grinding only becomes a common shaping technique in Africa during the Later Stone Age (Yellen, 1998; Bradfield, 2016). Likewise, at the end of the Late Paleolithic, past populations in North China appear to have specifically selected burnt bones, if not deliberately heated bone fragments in an anaerobic environment to change the color of the whole cortical bone rather than only its surface, to manufacture portable artwork (Li et al., 2020). Although bone discoloration can be achieved through multiple ways (e.g., Bradfield, 2018), a similar process has only been reported for the manufacture of blacken shell beads from Blombos Cave (d'Errico et al., 2015). Finally, a number of North Chinese sites suggests that the emergence of personal ornaments preceded the first occurrences of formal bone tools in the region by a few millennia. This is the case for instance at Shizitan, Shuidonggou and Zhoukoudian Upper Cave (Wei et al., 2016; Wei Y. et al., 2017; Song et al., 2017; d'Errico et al., 2018; d'Errico et al., 2021).

4 DISCUSSION

The present review on the origin and development of osseous technologies in the Old World, and the particular focus given to the Chinese archaeological record, sets the stage for a comparison of the cultural trajectories at a regional and global scales. When the timing and nature of the tipping points are considered, it becomes apparent that these trajectories are broadly similar. Despite an early appearance of bone tools in East and South Africa, evidence from China suggests that the first hominins whom dispersed in this region were carrier of a set of knowledge which allowed them to modify butchery and carcass processing by-products for technological purposes. The numerous reports from Early, Middle and Late Pleistocene contexts indicate this aspect of material culture remained in the toolkit of the populations that lived in China throughout this epoch.

From MIS9 onward, two lines of evidence indicates that the functional diversification of expedient bone tools observed in Europe is perhaps not restricted to this region, but could, in fact, constitute a trend that extends across the Eurasian continent. First, a clear difference emerges in the shaping of expedient tools during this period in China. Although direct percussion remains the predominant shaping technique, its application aims to produce long cutting edges rather then pointed objects. Second, the behavioural standardization illustrated at Lingjing is comparable to a similar trend documented in Europe for the manufacture and use of bone retouchers (Daujeard et al., 2014; Costamagno et al., 2018; Martellotta et al., 2020). The same is true for the tool types found at Lingjing, which bears numerous resemblances with those found at Schöningen for instance (Julien et al., 2015; Bonhof and van Kolfschoten, 2021). Collectively, these observations suggest that Lingjing, rather than representing an outlier in the Chinese archaeological record, likely provides a snapshot on a regional cultural trajectory that may become more and more comparable with the European one with future discoveries.

The last similitude refers to the emergence of formal bone tools. We now have ample clues in favor of a convergent cultural innovation throughout the Old World around 45 ka. The Chinese archaeological record shows this development is contemporaneously occurring in East Asia as well. Across the world, this cultural change appears closely linked with the development of hunting armatures and a paraphernalia of other tool types, and signals an increase complexification in prehistoric technological organization. It must be stressed here, however, that the emergence of formal tools didn't entail the abandonment of expedient bone tools by Upper and Late Paleolithic populations. Quite the contrary, formal bone tools augmented the pre-existing toolkit they inherited. This accretion process likely signals an increase reliance on complex technologies by these human groups (Kuhn, 2020). The easy access to workable skeletal remains from hunting and carcass processing activities, the lighter weight of bone technologies compared to lithic implements, their durability and maintenance properties (*sensu* Bleed, 1986; Bamforth, 1986) were likely key factors favouring the adoption of this lasting innovation by highly mobile hunter-gatherer populations.

Two differences stand out when comparing the cultural trajectories from China to those from the rest of the Old World. First, to this day, evidence for an "early" emergence of formal bone tools is restricted to the African continent between 90 and 65 ka. This phenomenon is even more peculiar when we consider the pattern of regionalization in tool type distribution and the fact that this category of osseous technology abruptly disappears from the archaeological record after 60 ka (see below). Second, when formal bone tools reemerge around 45 ka, the technical know-hows implemented for their manufacture show subtle, yet lasting, variation in their distribution. A potent example of this variation lies in the ubiquity of grinding used as a shaping technique in Asia and Africa, and its relative absence in other part of the world.

Based on the above review and regional comparison, future studies on osseous technology should address a number of research priorities. These research prospects are grouped below by main categories of bone tools. They primarily aim to fill the gaps in our understanding of this aspect of material culture to provide a complementary perspective to lithic tools in cultural evolution studies.

Thus far, research on "expedient tools" have mainly focused on bone retouchers, a tool type that lies at the interface between lithic and bone technologies. We now have ample evidence that early hominin technological adaptive systems also included the exploitation of skeletal elements for other activities. Therefore, future studies should be articulated along two main axes. First, more experimental programs must be implemented to test the criteria suggested to recognize intentionally modified osseous fragments (e.g., Backwell and d'Errico, 2004; Doyon et al., 2021). Such criteria would allow zooarchaeologists and taphonomists to quickly identify faunal remains that should be subjected to a thorough technological analysis. Second, and in parallel with the first axis, more use-wear studies, both experimental and archaeological, should be undertaken to establish the activities in which these tools served a purpose (e.g., Shipman and Rose, 1983; Baumann et al., 2020; Mateo-Lomba et al., 2020). The development of use-wear method in China, in particular, would allow archaeologists to move away from typological approaches when dealing with expedient tools (e.g., An, 2001). Indeed, a major setback of such classification systems, too often inspired by lithic typology, lies in the fact that these tool types carry a functional meaning that may not correspond to the activities for which they were used. Instead of reducing the development of osseous technologies to a succession of tool types, studies in cultural evolution should focus more on the choices made by past population regarding the selection of skeletal elements, the methods used to modify them and the role these objects fulfilled in the technological system. From a chronological standpoint, these two research axes should not be restricted to period preceding the emergence of formal bone tools; they must also be extended to more recent Paleolithic periods, i.e., Upper and Late Paleolithic, to depict a clearer picture on how different osseous technological adaptations co-evolved in time.

Two main research axes are also identified for the study of "formal bone tools." First, although these tools have historically received most of the attention in archaeology, owing in part to the ease to identify them and for their crucial role in establishing chrono-cultural timelines, the nature of the data available to address questions related to cultural evolution is fairly uneven at a global scale. While data stemming from the application of the *chaîne opératoires* concept is commonplace in Europe, its application to the Chinese archaeological record remains exceptional (for a review, see Yin et al., 2021). However, this tool allows to detail the decision process implemented by prehistoric groups for the manufacture and use of bone technologies. Variation in these decisions are extremely instructive; they can help define boundaries between groups carrying different sets of knowledge as well as establish whether or not interactions existed between these groups. These variations can also be correlated with environmental and/or social variables to better apprehend the mechanisms and processes at the origin of change in the different cultural adaptive systems. Second, regional- and global-scale syntheses using multivariate analyses are essential in the near future. In spite of being usually restricted to a single tool type (Stordeur-Yedid, 1979; d'Errico et al., 2018; Doyon, 2019; Doyon, 2020), these syntheses illustrate their aptitude to retrace cultural phylogenies, explore topic such as technological organization and population dynamics during the Pleistocene. Bone technologists may find inspiration in analogous projects undertaken to investigate the variation in personal ornaments (Vanhaeren and d'Errico, 2006; McAdam, 2008; d'Errico and Vanhaeren, 2015; Rigaud et al., 2015; Rigaud et al., 2018; Balme and O'Connor, 2019; d'Errico et al., 2021), and confront their results to other aspects of material culture to provide a nuanced outlook on topics such as cultural innovations and transmission during the Pleistocene. From a chronological standpoint, a key question that needs to be tackled relates to the circumstances surrounding the *circa* 15-ka hiatus in "formal bone tools" between their first emergence and disappearance in the African record, and their convergent reappearance across the Old World around 45 ka. Addressing such issue requires to confront multiple regional cultural trajectories and engage in a sustained dialogue with specialists from other disciplines, e.g., paleoanthropology, paleogenetic, paleoenvironmental sciences, etc., in an attempt to comprehend whether, and to what extent, changes in osseous–and other–technology throughout the Pleistocene match the complex dynamics reflected in the evolution of our genus.

AUTHOR CONTRIBUTIONS

LD designed the study. MS and LD conducted the study. LD wrote the initial version of the manuscript. MS and LD reviewed and edited the final version of the manuscript.

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Conservative Style, Liberal Production: Hemudu's Binary System for Maintaining its Scapular Shovel Tradition in the Southern Yangzi Delta, 7000–6000 BP

Liye Xie[1]*, *Casey Lun*[1], *Leping Jiang*[2] *and Guoping Sun*[2]

[1]*Department of Anthropology, University of Toronto Mississauga, Mississauga, ON, Canada,* [2]*Zhejiang Provincial Institute of Cultural Relics and Archaeology, Hangzhou, China*

In the past two decades, archaeological studies of knowledge and skill transmission for pottery and lithic production in preindustrial societies have significantly improved our understanding of how technological traditions were transmitted and how the transmission processes influenced technological persistence and changes. However, case studies of craft transmission for osseous technology are rare despite their equal importance to pottery and lithic industries in preindustrial societies. Our research fills the gap by examining early Hemudu Culture's (7000–6000 BP) scapular implements in the southern Yangzi Delta to understand the linkage between learning and maintaining the scapular shovel tradition in Hemudu's socio-economic context. We first traced the history of scapular tools to the precedent Kuahuqiao Culture (8200–7000 BP), then used published experimental results to identify the product traits pertinent to craft learning and infer Hemudu scapular shovel blades' learning and production patterns. Hemudu scapular shovels had a unique, complicated hafting style and an evidential raw material preference for old water buffalo scapulae. However, the blades' morphological details and technical solutions varied significantly. In addition, most finished products display manufacturing mistakes resulting from crafters' lacking skills, experience, and intervention. Practice pieces are rare compared to finished and used products. Although additional evidence implies that practice might have been more common than the studied sample suggested, it was carried out with less-than-ideal bones and insufficient for developing technical competency. We argue that the Hemudu societal norms for a scapular shovel applied only to the highly visible aspects of the implement. The shaft and ligatures could reduce the visibility of many manufacturing flaws on the shovel blade to reach the desired visual effect of the shovel. The shovel blades were made by household crafters emulating from an artifact or a memorized template but had insufficient training and practice in manufacturing. Communities of practice were minimal to nonexistent among the shovel makers; alternative mechanisms to maintain the technical norms or hold a high product standard were also lacking. Therefore, we concluded that the scapular shovels were less important as a technical implementation than a visual communicator of social identity. The binary system of conformist style and material

Edited by:
Yue Zhang,
Institute of Vertebrate Paleontology and Paleoanthropology (CAS), China

Reviewed by:
Amy Margaris,
Oberlin College, United States
Peng Lv,
Institute of Archaeology (CASS), China

***Correspondence:**
Liye Xie
liye.xie@utoronto.ca

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preference mixed with loose quality control in the shovel blade production reveals that social conformity and the associated learning pattern are circumstantial and fluid even for a community's iconic implement. Further research with other artifact types in Yangzi Delta would help shed light on whether similar learning patterns were applied besides the creation of scapular shovels.

Keywords: Hemudu Culture, Kuahuqiao Culture, bone tool, household production, Chinese archaeology, neolithic archaeology, craft learning, cultural transmission

INTRODUCTION

In the past two decades, archaeological studies of technology have gone beyond the inquiries of manufacturing techniques and objects' functions to explore technological practices' social and cultural dimensions. Experts of osseous technology, for example, have begun to address how object production, variation, and adoption related to raw material availability, choices, production patterns, manufacturing tradition, and group identities in the past (Choyke, Vretemark, and Sten 2004). This paper focuses on identifying the learning patterns of the bone shovel tradition in Hemudu Culture in eastern China to understand the linkage between learning and maintaining a technological tradition and its particular socio-economic context.

Theoretical approaches to cultural transmission range from the more positivist biological and evolutionary angle (e.g., Boyd and Richerson 1985; Richerson, Boyd, and Henrich 2010; Laland and Brown 2011; Mesoudi 2013; Reyes-García, Gallois, and Demps 2016) to social interactions (e.g., Keith 2005; Bowser and Patton 2008; Wallaert 2008; Schniter et al., 2015), and those that lie between (e.g., Laland 2008; Gintis 2011; Chudek et al., 2013). Results from ethnoarchaeological and experimental studies of craft transmission highlight how biological relatedness, social relations, identities, and economic structures shape craft learning patterns and how craft learning process feedbacks to technological tradition and its broader social, cultural, and economic situations (e.g., Greenfield 1999; Gosselain 2008; Herbich and Dietler 2008; Wallaert 2008; Derex, Godelle, and Raymond 2013; Ellen and Fischer 2013; Puri 2013; Schniter et al., 2015).

Craft learning occurs typically in the context of doing in a wide range of settings. The persistent material patterns in the archaeological record must have resulted from uninterrupted intergenerational learning (Crown 2014). To maintain a technological style, some form of teaching must be in place to sustain stability, consistency, and persistency through time (Tehrani and Riede 2008). Craft transmission can occur between parents and children, between experienced and inexperienced community members, and among peers. Parent-child transmission generally results in the most conservative and retentive family traditions but increases variance across families within a society (Ellen and Fischer 2013); the other two transmission pathways generate higher uniformity within a social group (Cavalli-Sforza and Feldman 1981). Craft traditions can also be conserved through communities of practice, where members are encultured into the social meaning embedded within decorations and techniques, recognizing their importance in maintaining group identity (Lave 1991; Wenger 1998; Dorland 2018). Communities may inadvertently or intentionally limit acceptable innovations and changes (Wendrich 2012); the pressure to conform results in technical, stylistic, and raw material consistency (Gosselain 2008; Herbich and Dietler 2008; Roux 2015). Crafts tied to community identity set cultural boundaries between groups. This sense of group identity can grow to the point where using out-group markers may evoke negative attitudes and discrimination (Nettle and Dunbar 1997).

Craft learning takes diverse forms, ranging from the least formal, such as self-teaching (by trial and error) and playing (Keith 2005; Bowser and Patton 2008; Gosselain 2008; Lancy 2012), to the more structured that integrates verbal instruction and hands-on demonstration, and to the most formal such as a contractual apprenticeship. Unskilled crafters with minimal training generally create products that are irregular in form (Crown 2001; Bamforth and Finlay 2008; Ferguson 2008), exhibit inconsistencies in production (Bamforth and Finlay 2008) and deviation from expected *chaîne opératoire*, or present predictable errors (Ahler 1989; Shelley 1990; Bamforth and Finlay 2008), and, in the case of stone tools, mis-hits and hammer marks (Pigeot 1990; Shelley 1990; Bamforth and Finlay 2008). Therefore, long-lasting craft traditions that exhibit high fidelity and/or standardization usually have an extended and intensive period of training (Gosselain 2008; Tehrani and Riede 2008; Wallaert 2008). However, training alone does not guarantee material culture consistency. How trainers respond to learner errors also significantly influences the persistence and variation of the end products (Greenfield 1999; Crown 2001; Wallaert-Pêtre 2001; Hasaki 2012). Constant error correction suppresses innovation and creativity and significantly increases product consistency. In contrast, a looser learning structure encourages innovation and product variation. Once learned, the production process that involves motor habits, particularly manufacturing techniques, tends to run deeper into the unconscious, thus is much more resistant to change than decorative styles (Gosselain 2000, 2008; Wallaert 2008; Thulman 2014; Roux 2015).

Identifying the pathways and forms of craft learning that contributed to the consistency and variations in the archaeological assemblage requires attention to the minuscule traits pertinent within the products' visual cues and manufacturing techniques. Most studies have been conducted on pottery making and, to a lesser extent, lithic production. Attempts to identify craft learning patterns for osseous technology from the archaeological record are sporadic (except

Zidarov and Averbouh 2014). However, as commonly used as pottery and lithic in pre-industrial societies, osseous tools were in the object repertoire that served technical needs and signified social identity. In an ongoing effort to understand craft learning and material patterns, we applied a cultural transmission framework to analyze the scapular shovel tradition in Hemudu Culture.

SCAPULAR IMPLEMENTS IN THE SOUTHERN YANGZI DELTA

Most scapular implements in China have been unearthed from the southern Yangzi Delta. The oldest unearthed scapular implements are from Kuahuqiao Culture (8200–7000 BP) with a small number in the subsequent Majiabang culture (7000–5800 BP) and the more elaborated ones in a much larger quantity from early Hemudu Culture (7000–6000 BP). This section synthesizes Kuahuqiao and Hemudu Cultures with information from the Kuahuqiao, Hemudu, and Tianluoshan sites—where most scapular implements have been discovered—to situate the Hemuduc scapular shovel tradition in the region's long-term and broader economic context.

Kuahuqiao, Hemudu, and Tianluoshan Sites

The Kuahuqiao site is the Kuahuqiao Culture type site situated on a hillside. The initial habitation surface is less than 1 m above the present sea level (W. Shi et al., 2008) and comprises Xiashu loess. Adjacent to the eastern rim of the habitation zone was an ancient lake at elevations of 1–2 m below the habitation surface (J. Shi 2009:14; ZPICHA and XM 2004:40-42); the lacustrine deposit in this area is waterlogged with excellent organic preservation. The site was occupied between 8200 BP and 7000 BP, a period between a freshwater inundation before occupation and a severe marine transgression that ended the occupation (Pan, Zheng, and Chen 2017). The site is estimated at 30,000 m^2; 1,080 m^2 have been excavated, with 2/3 of the excavated area covering the lacustrine deposit (ZPICHA and XM 2004:7-11). Most of the site has been destroyed by modern human activities, particularly large-scale clay exploitation for brick production. However, archaeological excavations in 1990 and 1999–2002 have salvaged remains of three small house structures, an earthen platform, a trench, and 25 pits (most for acorn storage). Pottery, some painted, includes mainly cooking and serving vessels, spindle whorls, animal remains, polished stone tools, bone tools, and artifacts of wood, bamboo, and antler were richly found. During the occupation, Kuahuqiao people relied principally on hunting (mainly deer and less frequently boar, water buffalo, and fowl), fishing, and gathering, complemented with rice cultivation and management of additional wetland and woodland plants, and domesticated pigs and dogs (ZPICHA and XM 2004; Fuller and Qin 2008; Yang and Jiang 2010; Zheng, Sun, and Chen 2012; Pan, Zheng, and Chen 2017).

The Hemudu and Tianluoshan sites are the only two Hemudu cultural sites that have been systematically excavated. Both sites are waterlogged with excellent preservation conditions. These two sites are 7 km apart, located in what is now the Yaojiang Basin. They were occupied soon after lands were exposed after the marine transgression that inundated the Kuahuqiao site, evidenced by the coastal sediments on top of which the initial occupation surfaces formed. These sites' ecological and geological settings were similar to those of the Kuahuqiao site, situated between lowlands and hills, adjacent to freshwater bodies but also near the ocean, and with immediate access to diverse natural resources present at different elevations (Pan 2011, 144). Like the Kuahuqiao people, the Hemudu communities consumed a broad-spectrum diet from hunting, fishing, and gathering consistent with low-level food production that included domestication of rice, pigs, and dogs and effective management of the ecosystems. Terrestrial prey were mainly deer, less frequently boar, water buffalo and fowl (Zheng, Sun, and Chen 2012; ZPICHA 2003). Osseous tools predominated the early Hemudu tool kit, and they were in more diverse forms and greater quantity than stone and wooden tools (Mou 1980; ZPICHA 2003, Table 7). The osseous tools mainly consist of hunting, fishing, and weaving implements. Scapular implements were not as abundant in number as bone arrowheads. Still, they have received much research attention due to their hypothesized relation to *si* agriculture, an advanced Neolithic farming technique involving tillage. However, the most recent functional analysis revealed that these scapular implements were used on an irregular basis to modify the margins of wetlands for cultivation and occupation (Xie et al., 2017).

Appearance and Adoption of Scapular Implements in the Southern Yangzi Delta

Kuahuqiao Culture (8200–7000 BP) has the oldest scapular tools in the region. Scapulae of appropriate animals (i.e. deer and water buffalo) were available throughout occupation(s) at Kuahuqiao; however, scapular tools did not develop until the latest stage of occupation during 7200 to 7000 BP (Xie 2014).

Excavations at Kuahuqiao led by the third author between 1999–2002 unearthed 24 scapular tools and 90 unmodified scapulae. Of the 24 tools, five have missed the diagnostic portions. Among the remaining 19 tools, 16 were crafted from deer scapulae, and most were expedient use of unintentionally broken scapulae as scrapers (**Figure 1A**). Only six deer scapular implements show evidence of intentional removal of unwanted portions, with the spine partially removed and a single edge created at the proximal end of the bone, diagonal to its long axis (**Figure 1B**). Two scapular implements were crafted from water buffalo: one is intact (**Figure 2A**), and the other is a dorsal portion of the bone's distal end (**Figure 2B**). Both specimens display thorough removal of the acromion spine and a vertical shaft hole from the top at the center of the glenoid. The intact specimen also has an opening in the medial side and a sharpened edge at the proximal end of the bone. An additional specimen was crafted from a carnivore scapula without evidence of utilization (details in section *The Kuahuqiao and Hemudu Manufacturing Techniques*).

Microwear analysis revealed that some of the scapular tools crafted from deer bone processed animal tissue while the water buffalo scapular implement was for earth working (Xie et al., 2017). Thus, related to warm-keeping and construction activities, these scapular tools were likely invented to cope with needs

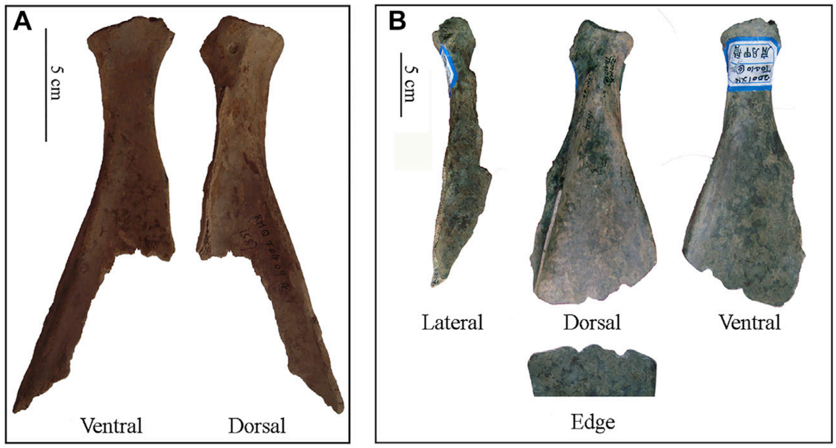

FIGURE 1 | Deer scapular implements from Kuahuqiao. **(A)** Sample expedient scapular scraper T0409 (4). **(B)** Sample scapular implement that is more carefully shaped, T0410 (6); function(s) not identified. Note that the dorsal and ventral faces in all figures of this article refer to the surfaces of the *bone*, which may not correspond with the dorsal and ventral surfaces of the *tool*. For example, the dorsal surface of a scapula refers to the posterior or back portion of the bone in animal anatomy, but it could have been used as a shovel's ventral surface facing toward the tool user (Xie 2018: Figure 1.1 for an anatomical scapula and an anatomical bone shovel).

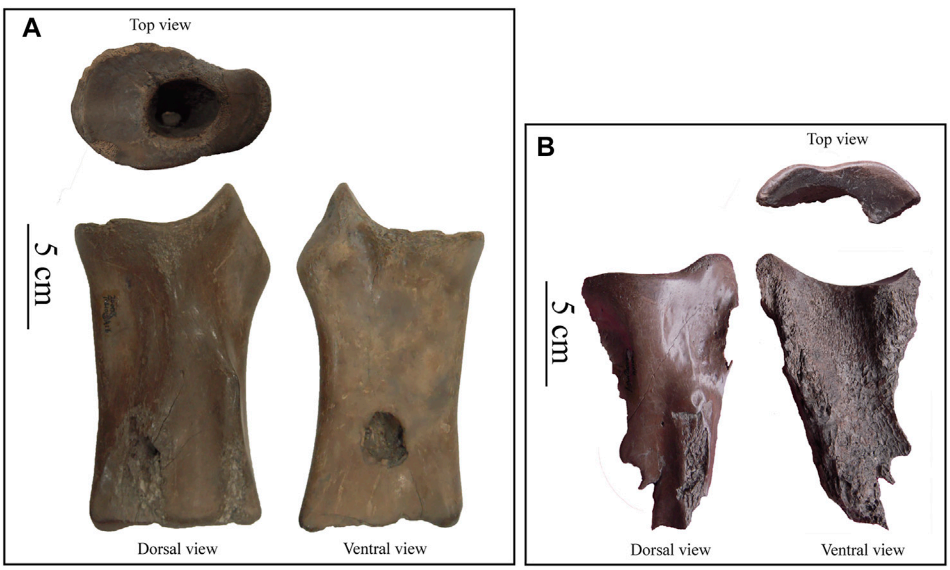

FIGURE 2 | Kuahuqiao water buffalo scapular implements. **(A)** 2001XKT0410 (5) A: 6, 13 cm long, 8 cm wide, with a 2.8 cm wide, 8.8 cm deep shaft hole in the center of the glenoid fossa of the scapula. **(B)** 2001XKT0410 (5) A: 7.

arising from settling in the open-air site of Kuahuqiao either seasonally or year-round.

Scapular implements continued into the subsequent period, 7000–6000 BP. A few scapular earth-working implements of the Kuahuqiao hafting style have been unearthed in early Majiabang Culture in the Lake Taihu area (Xie 2014). In contrast, the Hemudu populations on the Ningshao Plain used scapular implements crafted from water buffalo and deer bones to a greater extent for over a millennium (Xie et al., 2017). The scapular implements crafted from deer bone reflect minimal modifications and a broader range of uses than those fabricated from water buffalo bones. Most deer scapular implements of Hemudu Culture show partial removal of acromion spines, slight modifications on the sides of the necks, and a two-pronged edge. Most two-pronged edges were formed from fractures likely resulting from hunting (compare **Figure 3A** with **Figure 3B**). Only a couple of such edges show a regulated contour that might have been intentionally shaped (e.g., **Figure 3C**).

The implements crafted from deer scapulae were mainly used for processing hide and bark and occasionally for light earth-working tasks such as relocating soil (Xie et al., 2017). On the

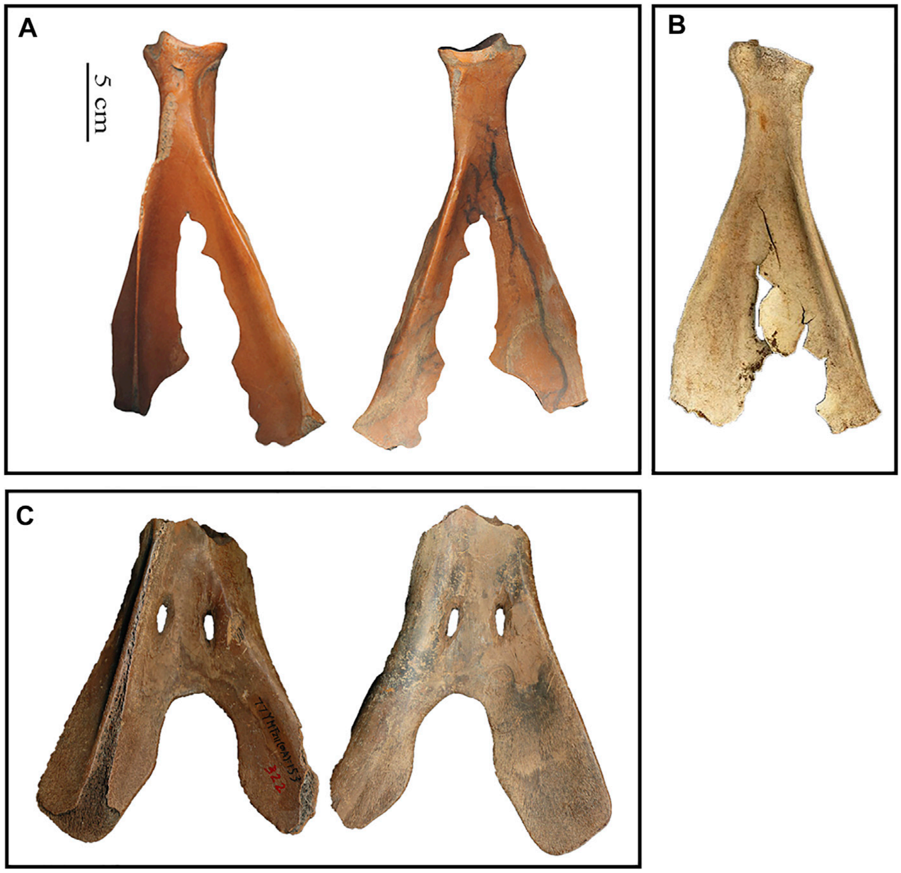

FIGURE 3 | Humudu culture deer scapular implements. **(A)** HMD 332 (dorsal and ventral views), with partial removal of the acromion spine, minimal modification on the sides of the neck, and a two-pronged edge likely resulted from hunting; **(B)** Unmodified caribou scapula from Palangana, Alaska (ventral view); housed in the Zooarchaeology Lab at the University of Arizona in Tucson; **(C)** HMD 322 (dorsal and ventral views), with a two-pronged edge likely shaped intentionally.

other hand, the Hemudu scapular implements crafted from water buffalo bones were primarily used for earth working in agricultural and construction contexts (Xie et al., 2017). The water buffalo scapular implements show complete or near-complete removal of the acromion spine and part of the posterior border that runs alongside the acromion spine. Most noticeably, these implements display sophisticated modifications for hafting, including 1) a groove on the ventral face with two perforations, 2) deep notches on the lateral sides of the scapular neck, which are usually transversely scored through, and 3) flattened projecting portions around the glenoid to ensure effective lashing (Xie 2018). These water buffalo scapular implements were hafted as shovels with the ligatures lashed across the sockets and entirely around the necks to fasten the shafts tightly (**Figure 4**).

The Hemudu style of groove-perforation-scored notch design for earth-working implements is more elaborate than alternative hafting designs observed in other cultures across the globe. For example, in Kuahuqiao and Majiabang Cultures in Yangzi Delta and pre-industrial societies in Europe and America, the modifications include only removing the acromion spine, the posterior border of the bone and very light modification on the sides of the necks, occasionally with a socket created at the center of the glenoid or an opening created on the ventral surface of the bone (Xie et al., 2017). Compared to the simpler designs, the Hemudu hafting design fastened the blades to the handles much more securely, likely as a reaction to hafting failure in the increasingly arduous earth-working tasks in the Hemudu site due to the sticky soil condition (Xie et al., 2017; Xie 2018). However, the Hemudu crafters overdesigned the tight fastening elements. The excessive removal of a large quantity of the strongest (cortical) material required more effort and time to manufacture while significantly weakening the implements, causing consistent breakage along the weakened points of the tools during the implements' use life (Xie et al., 2017). Xie has previously proposed two technical factors to explain the emergence of these overly sophisticated scapular tools: 1) the need for a tight joint and 2) the presence of advanced ground stone adzes, axes, and chisels that made the modifications relatively easy to accomplish (Xie 2014; Xie 2018: Fig 10 for sample stone tools unearthed from Tianluoshan suitable for fabricating scapular shovels).

Statistical analysis of the width and rugosity level of the scapulae neck show that scapulae from old adult wild buffalo

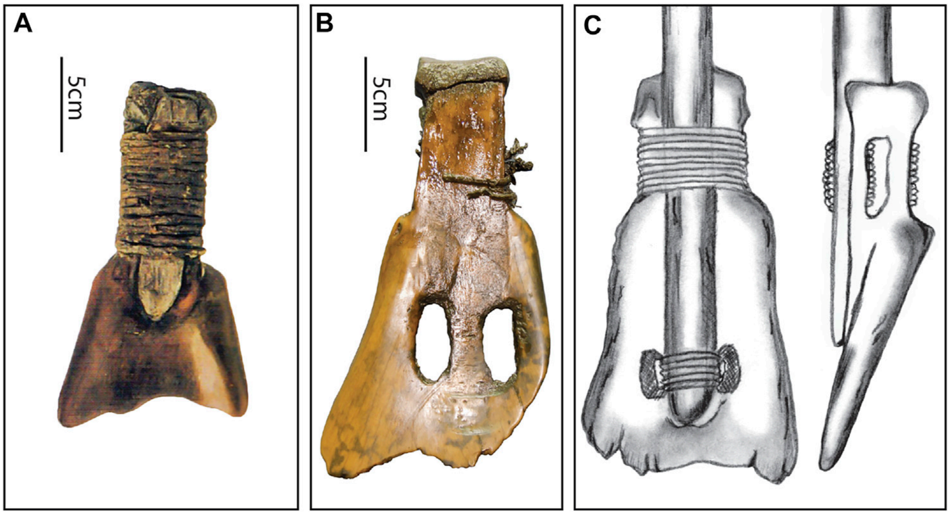

FIGURE 4 | Hemudu hafting styles for scapular shovels. **(A)** HMDT224 (4) B:175 with a small portion of the shaft and ligatures lashed across the socket and entirely around the neck (after ZPICHA 2003: plate 26–1). **(B)** TLST302 (8): 3 with partial ligatures across the socket. **(C)** Reconstructed hafting method followed Mou 1980: Figure 2 and Xie et al., 2017:Figure 4.

was strongly preferred for crafting the Hemudu scapular earth-working implements and that Hemudu people likely took these heavy bones from kill sites but rarely transported scapulae from younger buffalo (Xie and Stiner 2018). The larger dimensions and greater robustness of old buffalo bones than those of deer and younger buffalo grant them the ability to withstand the abrasion and battering in the local soil conditions.

However, as discussed below, our research reveals that both the unique hafting style and the raw material preference served purposes beyond techno functional considerations: they visually communicated the Hemudu people's social identity.

The Kuahuqiao and Hemudu Manufacturing Techniques

As aforementioned, most Kuahuqiao specimens were expedient use of unintentionally broken deer scapulae. The manufacture of the six lightly modified deer scapulae involved a hammerstone smashing part of the acromion spine and a grinding media shaping the functional edge at the proximal end of the bone. The production of water buffalo scapular implements is unclear due to the absence of diagnostic traces blurred from hafting friction. However, based on the techniques available at the time, our educated guess is that the production most likely involved a ground stone chisel or adze in creating the hole and the opening and a grinding media to sharpen the functional edge.

A sample of an intentionally modified non-tool at this site reveals additional information of an intended trial during the process of technological innovation. This implement, 2001XKT0411 (5)A:43, has a shaft hole 1.5–2 cm in diameter and 1.4 cm deep at the center of the glenoid (**Figure 5**). Unlike a functional tool, this artifact lacks other modifications and traces from hafting and use (compared **Figures 2**, **5**). The shaft hole was crafted with the assistance of burning, leaving evident traces and resultant cracks around the hole's entrance. Of all specimens unearthed from the Kuahuqiao, Hemudu, and Tianluoshan sites, 2001XKT0411 (5) A:43 is the only example manufactured by burning. As the technique turned out to cause cracks, the sample was not further modified or used. It is also the only example fashioned from a carnivore scapula, and it is much smaller (15.5 long, weight 70 g) and thinner than the scapula of a water buffalo or a large deer. Together these led to the conclusion that this implement represents an unsuccessful trial in manufacturing technique, tested with similar but less-than-ideal raw material. Alternatively, this implement could have been a child's toy.

Hemudu scapular implements' sophisticated hafting modifications required a much more complicated reduction procedure. Results from replication experiments identified the optimum reduction sequence and the most practical technologies in each reduction step to eliminate accidental breakage during scapular shovel production (Xie 2018). The optimum reduction sequence with the ideal technologies is the following. First, remove the spine and proximal end with a hammerstone. Second, use a hafted groundstone axe to cut away unwanted mass from the scapular neck to fashion the notches. Third, flatten the interior side of the distal end with a coarse-grained abrader. Fourth, use a groundstone chisel with a hammerstone to create the grooves before perforations. Fifth, score through the notches with an awl. And finally, sharpen the edge with a coarse-grain abrader.

The manufacturing traces observed on the archaeological samples suggest that these techniques were among the diverse technical solutions the Hemudu craftspeople employed in scapular implement production. See Xie (2018): Supplementary Table 1 for inferred manufacturing techniques of the scapular earth-working implements from the Hemudu and

FIGURE 5 | An unsuccessful trial with burning to create a shaft hole: T0411 (5) A:43 from Kuahuqiao (top and dorsal views).

Tianluoshan sites and further discussion below in the *Results* section concerning Hemudu people's craft learning and production pattern for scapular shovel production.

MATERIALS AND METHODS

We examined all worked scapulae and discarded fragments from the sites of Hemudu and Tianluoshan, including 1) 93 specimens housed at the Hemudu Museum, representing about half of all scapular implements unearthed from the Hemudu site in the 1970s; 2) 62 scapular tools housed at the Tianluoshan Archaeological Station, representing 95% of scapular implements excavated from the Tianluoshan site between 2004 and 2011; and 3) a comparative sample including all 701 unmodified scapulae and all faunal fragments larger than 2 cm unearthed from the Tianluoshan site (**Table 1**). The Hemudu Museum collection mainly has relatively intact and visually appealing specimens selected from the 1970s' excavations, whereas the Tianluoshan assemblage includes everything systematically collected from recent excavations. Therefore, we relied on the Tianluoshan collection for complementary clues for reconstructing the broader picture. All examined specimens are typically uncovered together with objects for daily use or from refuse in the habitation areas. There are no recognized differences between the distributions of worked scapulae and unmodified ones.

Cervidae (deer) and Bovidae (bovids) were the principal sources for the scapulae; occasionally, scapulae sourced from members of the Ursidae were also used (**Table 1**). Based on the bone's dimension and concerning the archaeological fauna (Wei et al., 1990; Zhang et al., 2011), cervids *Elaphurus davidianus* (Père David's Deer), *Cervus unicolor* (Sambar Deer), and *Bubalus* sp., probably *B. Mephistopheles* were the deer and bovid whose scapulae were crafted into tools at Hemudu and Tianluoshan. We use the common names of the animals in the discussion for simplicity's sake.

Our research employed results from the replication experiments reported in Xie 2018 to identify the product traits pertinent to crafting learning and use these indicators to analyze crafting competency displayed in the archaeological sample. In addition, we calculated the Coefficient of Variation (*CV*) to measure the levels of morphological variation of hafting modifications in the archaeological assemblage. *CV* expresses the variation as a percentage of the sample standard deviation to the sample mean and has been proven to be the most robust, suitable statistical means for assessing product variation (Longacre 1999; Eerkens 2000; Eerkens and Bettinger 2001) and inferring specialized/non-specialized craft production (e.g., Longacre 1999; Roux 2003). Furthermore, we examined the practice pieces in the archaeological sample to further understand craft learning in the Hemudu society.

RESULTS

Xie 2018 reconstructed the technical details of bone shovels and their manufacturing methods in Hemudu Culture using replication experiments. The following three paragraphs briefly reiterate the experimental observations regarding crafter's technical competency to set the stage for further discussions on the archaeological observations concerning Hemudu's cultural transmission system for bone shovel production. Most archaeological observations presented in this section have not been published elsewhere, with a few exceptions indicated with citations.

TABLE 1 | Numbers of scapula specimens examined.

Site	Scapular tool						Unmodified scapulae
	Total	Water buffalo	Deer	Bear	Carnivore	Undet.	
Hemudu	93	63	20	2	0	8	0
Tianluoshan	62	15	16	0	0	31	701

Note: the "undet" (undetermined) source animals are still mostly deer and water buffalo, but they cannot be named as one or another because their diagnostic portions are missing.

Xie and three adept crafters started to replicate the bone shovel after Xie had carefully gone over the archaeological collections once. The experimental results indicate that the *adequate* level of know-how for producing a product similar to a typical Hemudu bone shovel without breaking it is low because the quality of bone is stable and predictable. With a bit of formal or informal training and less than five trials, an adept person familiar with the mechanical properties of bone could craft a typical Hemudu-style scapular shovel of a workable quality from a large cattle scapula. The finished products' quality varies depending on the person's innate dexterity and bone-working experience; however, the quality is generally at the lower end of the spectrum.

Common errors in the early stage of the experiments included using less-than-ideal raw materials (i.e., scapulae from young cattle instead of old individuals), improper anvil arrangement, mislocation or disproportionate dimension of modifications, inappropriate reduction sequences, and failure in force control. Using a hard anvil, reversing specific steps of the optimum reduction sequence, and applying a force of improper amount or from the wrong angle often caused accidental breakages or, at best, produced flawed products. For example, one failure in force control in the experiment created a partially missing straight side of a hafting notch displayed in Xie 2018:Figure 7.1. Using scapulae of young buffalo and mislocating or disproporting the dimensions of modifications usually produced products that either did not look right or performed awkwardly.

Producing high-quality products free of manufacturing flaws would have taken much more experience. In particular, the accurate locations and proper proportions of modifications are not readily transferrable between young animals' scapulae and the larger and more robust scapulae from old adults. Even with the right scapulae, Xie's memorized template after examining the archaeological specimens was inaccurate for object reproduction. Thus she had to keep either a scanned photo or an actual model object in view to determine the accurate location and dimension for each modification. Even so, it took Xie a dozen more trials to develop the ability to accurately adjust the locations and dimensions of the hafting modifications according to a scapula's dimension. However, once developed, most of the knowledge for high-quality production is transmittable to a novice with verbal instruction and/or accurate guide lines on the scapula. Precise force control appeared to be the only aspect that each crafter must practice to accomplish.

High Morphological Variation Despite Consistent Object Style

The overall hafting style of scapular earth-working implements appears consistent during the Hemudu period; however, the morphological details of the hafting modifications vary significantly (**Figure 6**; **Table 2**). Here, morphological details refer to the hafting modifications' relative dimensions and relative locations. These are calculated as the ratios of a modification's dimension (e.g., a hafting groove's width) or its location (e.g., the perforations' distance from the glenoid) to the smallest length of the collum scapulae (SLC), the only original dimension that generally survived the tool-manufacturing process. Such relative measurements are more accurate for assessing morphological variance because the exact measurements can be reflective of the varying original dimensions of water buffalo scapulae. Moreover, relative measures capture inaccurate locations and disproportion of hafting modifications in relation to the scapular dimension, indicators of lacking experience highlighted above.

As the results listed in **Table 2** indicate, the *CV* values of the scapular implements' hafting modifications at the Hemudu site range 9–25% and averaged 19%. This level of variation is close to that of English Mesolithic microliths with *CV* values ranging between 5 and 39% and averaging 19% (Eerkens 1997, 1998), which are interpreted as representing low variation (or high standardization) for microliths (Eerkens 2000:667). However, we consider a close *CV* range among the Hemudu scapular spades an indication of high variation.

Raw materials and technological systems significantly influence the *CV* values representing low or high variations (Eerkens 2000; Eerkens and Bettinger, 2001). We argue that the *CV* range indicating low product variation of scapular earth-working implements should be much lower than microliths but probably closer and slightly higher than pottery. This assumption is based on the fact that raw materials that are more difficult to control for transformation and modification tend to inflate *CV* values (Eerkens and Bettinger, 2001). Bone material is easier to handle than stone but more challenging to control than clay. Scapulae are easier to manage than stone because 1) the original dimensions and shapes of water buffalo scapula provide a great frame of reference to the dimensions of reduction, 2) the dimensional range of the scapulae provides a narrow window for dimensional error of reduction, and 3) as Xie 2018 pointed out, scapulae's quality is more consistent than stone, rendering predictable fracturing properties across pieces and minimizing manufacturing errors and failures during reduction. In addition, the *CV* values of scapular implements are more comparable to those of pottery than those of microliths because the measurements of scapula hafting modifications and pot dimensions indicate the original dimensions. Microliths dimensions, on the other hand, may have been altered through use and reshaped. While we are confident that

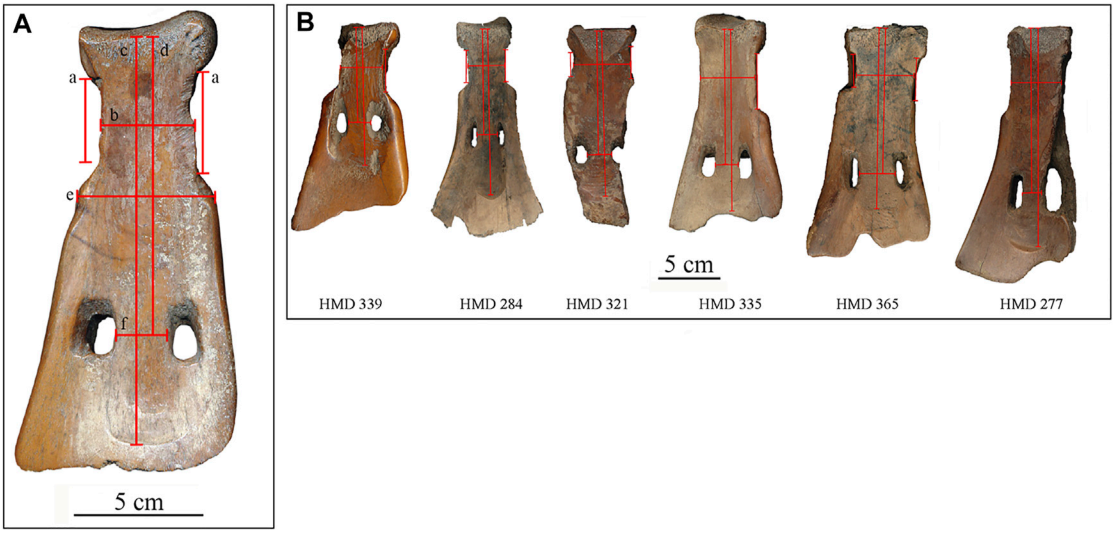

FIGURE 6 | Product variation in Hemudu scapular earth-working implements. **(A)** Measurement points for analysis of morphological variation (illustrated with HMD 271): a. Length of notch; b. Width of groove; c. Length of groove; d. Distance between the glenoid and the perforations; e. SLC (the smallest length of the collum scapulae); f. Distance between perforations. **(B)** Examples of morphological variations in hafting modifications despite consistent object style.

TABLE 2 | Levels of product variation measured by coefficient of variation (*CV*).

	Distance between perforations	Distance between the glenoid and perforations	Groove width	Groove length	Notch length
SLC	$\bar{X}$ = 0.07, S = 0.31, *CV* = 22.58, *N* = 39	$\bar{X}$ = 0.11, S = 0.59, *CV* = 18.64, *N* = 33	$\bar{X}$ = 0.11, S = 0.59, *CV* = 18.64, *N* = 35	$\bar{X}$ = 0.06, S = 0.44, *CV* = 13.64, *N* = 28	$\bar{X}$ = 0.14, S = 0.55, *CV* = 25.45, *N* = 28
Groove width	$\bar{X}$ = 0.11, S = 0.53, *CV* = 20.75, *N* = 49	$\bar{X}$ = 0.08, S = 0.35, *CV* = 22.86, *N* = 40	—	$\bar{X}$ = 0.04, S = 0.27, *CV* = 14.81, *N* = 38	—
Groove length	—	$\bar{X}$ = 0.07, S = 0.76, *CV* = 9.21, *N* = 40	—	—	$\bar{X}$ = 0.06, S = 0.25, *CV* = 24, *N* = 31

working in the medium of bone lends itself to a *CV* between stone and pottery, future experiments need to verify the *CV* ranges of lithic and ceramic products with expanded datasets and specify the *CV* range of bone tools to validate this argument.

Replicated Manufacturing Mistakes

Some morphological variants were caused by failing to apply the right amount of force during the manufacturing process. For example, HMD 283 and HMD 328 display straight sides resulting from misdirected cuts (**Figures 7A,B**). Such straight sides are fragile because all compact bone is removed from the sides of the neck and the glenoid, and they cannot hold lashing as well as the notches do. Interestingly, a few Hemudu and Tianluoshan specimens show this "style" without evidence of misdirected cuts. Some other specimens show an in-between style: with compact bone on the sides of the glenoid removed while retaining very shallow notches on the sides of the neck, and sometimes the shallow notches were crafted only on the ventral surface. Sometimes the straight sides were further notched to create a morphological similarity of notched sides (e.g., **Figure 4B**, **Figure 7A**). We suspect that these samples resulted from either modelling after a flawed specimen or simply from failings of morphological memory. No matter which reason best explains the variation, these variations reflect a group of inexperienced craftspeople.

Additional mistakes exhibited by archaeological specimens are diverse and less common. For example, some specimens display prominent, inaccurate locations or disproportions of the hafting modifications. The perforations of TLST302 (8):3 are too large (**Figure 4B**). HMD 271 retains two hafting grooves, with the longer one being mislocated and, therefore, corrected by creating a shorter one (**Figure 7C**). HMD 367 has a highly long notch on one side of the neck that was fixed by adding a shorter notch before completion. The compact bone on this side of the neck is wholly removed, forming a straight side instead of a notch (**Figure 7D**). This is another example of poorly managed force control in the notching process. The directions of perforations are tilted to one side. The overall quality of all modifications suggests the production of a naïve craftsperson. However, intensive hafting wear indicates that the implement had been used, and the missing edge segment probably resulted from use damage. HMD 368 has extremely deep notches on the sides, and so the

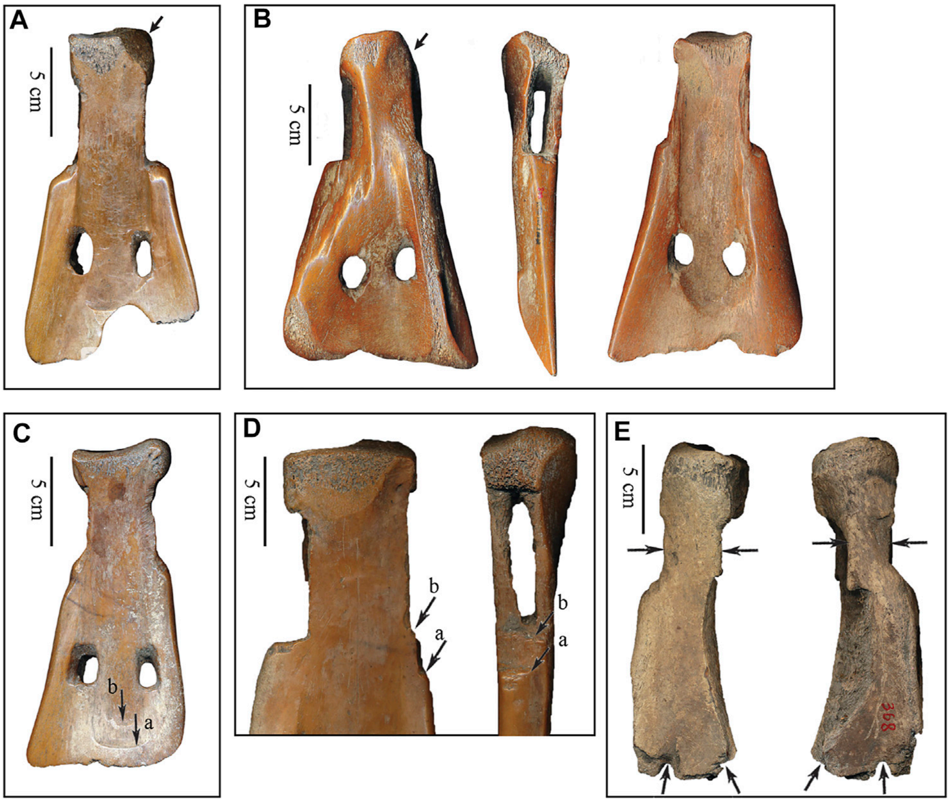

FIGURE 7 | Examples of manufacturing mistakes. **(A,B)**. misdirected cuts: HMD 283 and HMD 328 (dorsal, lateral, and ventral views). **(C)** HMD 271 retains two hafting grooves, with the longer one (a) mislocated and therefore corrected by the creation of a shorter one (b); **(D)** The distal portion of HMD 367 (ventral and lateral views) shows a long notch (a) corrected by the addition of a shorter notch (b); **(E)** HMD 368 (ventral and dorsal views) displays a few mistakes: an extremely deep notch which created an excessively narrow and weak neck (blue arrows) and also caused breakage along one border of the scapula; perforations (yellow arrows) too far from the articulated end, leaving insufficient material for use and eventually leading to edge breakage.

remaining neck is excessively narrow. Excessive notching of the side caused breakage along one border of the scapula (**Figure 7E**). HMD 368 also contains perforations too far from the glenoid and thus might have been too close to the edge, leaving insufficient material for use and locating the perforations at a much thinner section of the blade, eventually causing the edge breakage. The edges of the notches are rounded, indicating that the implement was once hafted and likely used.

Diverse Technical Solutions During Production

The Hemudu crafters employed a diverse array of technical solutions during scapular implement production. In particular, the spine was removed by abrading, cutting/smashing, sawing, or a combination of cutting and grinding. The notches were produced either by cutting, abrading/sawing, or a combination of cutting-abrading/sawing off unwanted bone mass from the scapular neck. The grooves were created by chiselling, whittling/shaving, sometimes in combination with abrading. Finally, the perforations were made by chiselling and occasionally expanded by drilling (Xie 2018: Supplementary Table 1).

In addition, some objects' manufacturing solutions show more control than others. For example, some but not all hafting grooves and notches display a straight distal end, indicating that a guide line was created either by the crafters to help control the propagation of fracture or by a tutor to define the location and dimension of the modification for a pupil. Interestingly, the guide lines are often not at the ideal places.

Furthermore, the archaeological assemblage indicates inconsistent manufacturing procedures, some of which are against the optimum reduction sequence. For example, about a quarter of the archaeological specimens were perforated before grooving, resulting in accidental breakage during manufacture.

Low Ratio of Practice Pieces to Finished Products

The finished products, including the flawed implements, were nonetheless used in Hemudu Culture, suggesting that they were produced for use and unlikely to have been products of training or trial pieces. Archaeological specimens with evidence of being practice pieces are rare compared to the number of finished and used products. Moreover, even when the practice was carried out, it was likely on an individual level

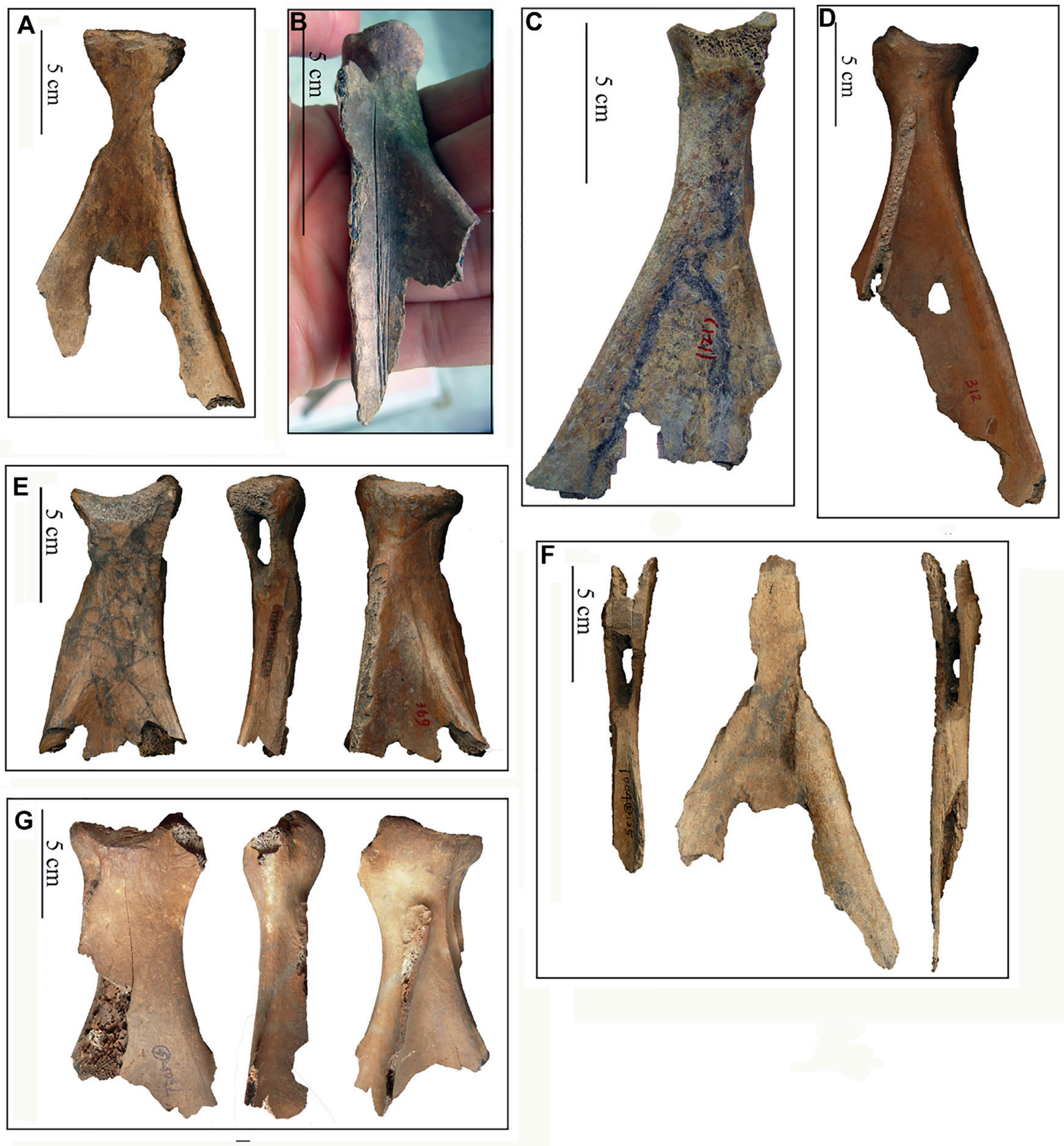

FIGURE 8 | All practice pieces in the studied sample. **(A)** HMD 311 with extremely deep notches on the sides of the neck, causing breakage of the scapular border. **(B)** TLST104 (6):G360 with incised lines to both sides of the acromion spine. **(C)** TLST302 (6):G121 with the projection of the articulating end on the ventral surface and the acromion spine partially removed. **(D)** HMD 312 showing improper approaches to perforation, also at inappropriate locations. **(E)** HMD 369 with perforations skewed to one side of the blade, causing lateral breakage. **(F)** TLST004 (5): 25 with two sets of scored notches. **(G)** TLST305 (5): SGS1 with the side of the neck slightly modified, the acromion spine removed, and the ventral surfaces of the glenoids cut and ground.

and informal. Only four of 62 scapular implements unearthed from the Tianluoshan site and three of 93 studied specimens from the Hemudu site appear to be practice pieces (**Figure 8**). Unlike the finished products often crafted from old buffalo scapulae, most manufacturing practices were carried out with deer scapulae, and most products were unfinished or finished but used in a way that did not require those modifications.

Two bear scapulae (HMD 287 and HMD 326) with all the modifications of a typical Hemudu-style shovel (**Figure 9**) look awkward for earth working and, therefore, could have been practice pieces. However, they were more likely shovels that played symbolic as opposed to practical roles in earth-working activities. Both "shovels" show rounding on the edge and the hafting area, despite the blades' overall unsuitable shapes for crafting into a shovel. HMD 326 even displays soil-derived wear along the edge (Xie et al., 2017:Table 6); the cause of the traces on HMD 287's edge is unclear.

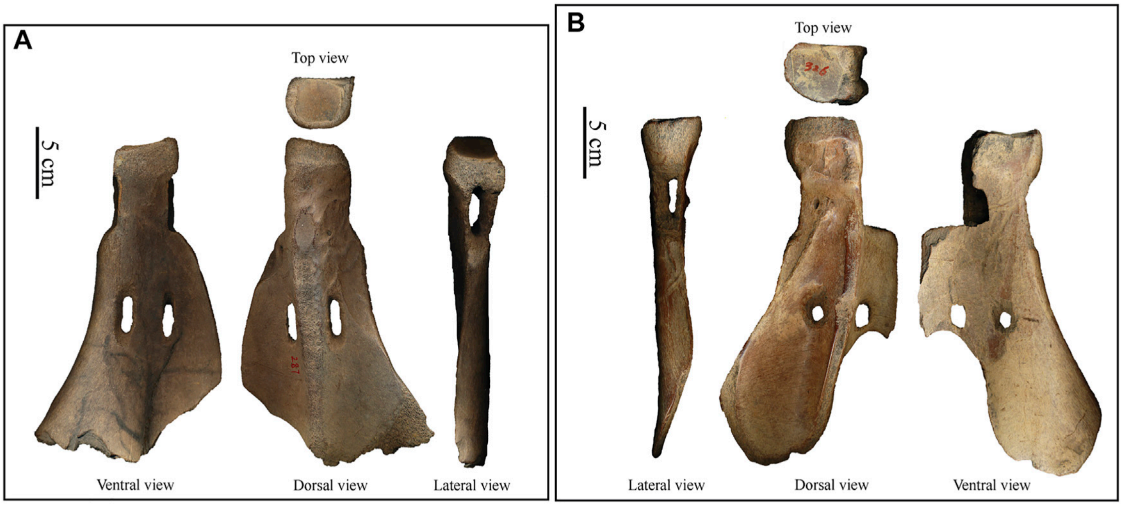

FIGURE 9 | Bear scapular implements from the Hemudu site. **(A)** Hemudu 287. **(B)** HMD 326. Both have all the modifications of a typical Hemudu-style shovel and show rounding on the edge and the hafting area, despite the blades' overall unsuitable shapes for crafting into a shovel.

DISCUSSION

The results discussed above indicate that the production of scapular spades may have been carried out by self-sufficient household craftspeople rather than craft specialists. Particularly, these results include the presence of 1) low standardization of final products reflected in varying morphological details and manufacturing solutions, regardless of consistent object style; 2) unequal, low to moderate levels of manufacturing skills observed on the finished products that were used regardless of differences in quality; and 3) replicated mistakes and a low number of practice pieces indicating limited training and practice.

Low Standardization of Final Products Resulted From Inexperienced Production

The *CV* values of the scapula modifications are higher than expected for specialized production. Ethnoarchaeological studies of Indian, Spanish, Filipino, and Chinese potters reveal that pots bear 2–4% of *CV*s when produced by full-time specialists and 6–9% of *CV*s by part-time specialists (Longacre 1999; Roux 2003; Fu 2018); these *CV* ranges are lower than that of scapula modifications. Even the *CV* ranges of pots made by beginners of specialists (7–17%) and non-specialists (10–14%) (Longacre 1999) are lower than or at the lower end of the *CV* range of scapula modifications. Therefore, we consider the product variation among Hemudu scapular implements to be relatively high.

Many factors can lead to high morphological variation among scapular earth-working implements, including infrequent production (Eerkens 2000; Eerkens and Bettinger 2001), low degree of skill (Costin and Hagstrum 1995), high manufacturing tolerances for deviation from a standard template (Ferguson 2008:64), purposive expression of idiosyncrasy (Eerkens and Bettinger 2001), or a combination of these factors. In addition, everything else being equal, a greater number of producers can result in higher product variation within an archaeological assemblage (Costin 1991; Fu 2018). Furthermore, self-teaching relying on trial-and-error can introduce greater product variations than social learning methods that involve specialists' guidance.

Purposive expression of idiosyncrasy can be ruled out in the Hemudu case because this often happens in creative artwork or similar circumstances when individual producers make a conscious effort to differentiate their products from those of others, which would have resulted in a *CV* more significant than would occur when production is entirely random. A *CV* above 58% has been suggested as an indicator of purposeful diversification (Eerkens and Bettinger, 2001). On-site training by specialists is also unlikely to be responsible for the high variation among the Hemudu scapular implements because no workshop has been found at the Hemudu and Tianluoshan sites for scapular implements. While the absence of a workshop could have resulted from sampling biases in excavation and challenges in identifying such features in the field under a water-logged condition, additional evidence suggests that the high morphological variation more likely resulted from the implements' production pattern. The following sets of evidence jointly led us to conclude that the scapular implements were produced by many unprofessional, inexperienced individuals representing self-sufficient household production: 1) diverse technical solutions employed in scapular tool production suggesting emulation rather than imitation; 2) replicated mistakes revealing a lack of skills, experience, and intervention; 3) heavy utilization of all finished products, including the ones full of manufacturing flaws; and 4) a minimal number of manufacturing practice pieces.

Emulation Rather Than Imitation

The technical variations, including diverse technical solutions and varying levels of procedure management, reflect emulation (i.e. focusing on the outcomes of the manufacturing actions) rather than imitation (i.e. copying the specific set of actions or apprenticeship transfer of actual manufacturing techniques). Furthermore, replicated mistakes and the scarcity of practice pieces suggest that emulation most likely used an artefact as a template or reproduced from a memorized template with limited skills, experience, and little intervention.

Lithic and ceramic studies have demonstrated that emulation relies on the visuals of the final product and generally creates high variance within assemblages (Tehrani and Riede 2008). Experimental results also confirm that crafters who have only the final product to emulate significantly deviated from the template and produced more variance than social learners and process-copying (Derex, Godelle, and Raymond 2013). Through emulation, the traits that end up being the most conserved are those that are highly visible on the final creation (Roux 2015). Emulation often happens when intervention and communities of practice are lacking (Berg 2015).

Replicated Mistakes and Scarcity of Practice Pieces Suggesting Inadequate Training, Intervention, and Practice

The manufacturing mistakes observed from the archaeological scapular implements include all typical novice or unskilled craftspeople indicators Xie witnessed during her replication experiments' early stage of self-training in becoming a specialist for crafting Hemudu scapular implements. Certainly, the learning circumstances of the Hemudu craftspeople differed from the researcher: the Hemudu craftspersons may have been mentored by artisans with richer experience, but they may not have had the chance to observe as many artifacts as Xie did carefully. However, the similarities in the mistakes still suggest that many Hemudu craftspeople may have produced their implements according to morphological memory or a hafted shovel and did not repeat production even when final products turned out to be flawed. This evidence suggests that the craftspeople only occasionally handled and produced the shovel blades. After all, people working with standard objects daily would have had more accurate mental images of the correct size and shape for a particular object (Eerkens 2000).

Repeated errors in the archaeological assemblage indicate intervention was limited to nonexistent. One may argue that a few artisans might have been better trained and become specialists who produced the relatively high-quality products present in the archaeological assemblage. However, we contend that these were more likely craftspeople with the better natural ability or perhaps who had more practice than the bulk of these craftspeople because archaeological evidence does not (yet) support the hypothesis of the presence of a specialized training system. As mentioned earlier, the knowledge related to accurately locating the spots and proportion of hafting modifications in relation to scapular dimension takes a great deal of experience to accomplish; however, once obtained, the knowledge is easily transmittable to a novice with verbal instruction and/or with accurate guide lines on the object.

Alternatively, infrequent production in the society may have resulted in lacking experienced producers, so even the most experienced who might serve as trainers or consultants did not reach technical competency. The fact that guide lines were rare and often located at less-than-ideal places indicates that even the crafters who created them had not reached technical competency. The low ratio of practice pieces to finished products and the utilization of many flawed products suggest that crafters did not practice manufacturing adequately before crafting actual tools.

Certainly, the unearthed sample may have underrepresented practiced pieces. Of 701 unmodified scapulae unearthed from Tianluoshan, 690 were identified to species, but only one fragment, a scapular proximal end, belongs to buffalo (Xie and Stiner 2018:652). The almost absence of unmodified buffalo scapulae and the scarcity of scapular implements crafted from young adult and prime adult buffalo in the villages significantly contrast with the fact that these buffalo were the primary target of the hunters (Xie and Stiner 2018:651). These missing buffalo scapulae could have been used for manufacturing practices somewhere else and abandoned there, such as the kill sites or unexcavated areas of the villages. Nonetheless, practicing with these less-than-ideal scapulae must not have been sufficient for accomplishing the technical competency for crafting a high-quality shovel from the larger and more robust scapulae of older buffalo.

Overall, the unearthed finished products were evidently produced by inexperienced craftspeople with only low to moderate skill levels. Further, since the manufacture required axes and chisels that could be considered injury-prone for children and teenagers, the crafters likely involved only adolescents and adults.

High technical variation, low to moderate manufacturing skills, and evidence of insufficient manufacturing practice jointly led us to conclude that high product variation among the scapular earth-working implements was caused by the participation of many group members in production despite their inexperience, most likely representing self-sufficient household production. Parent-child intervention might have existed; however, most crafters were inexperienced. While self-sufficient household production was sustained through emulation, frequency-dependent bias toward bone spades reflects the majority's preferences across society. In other words, crafting mostly relied on trial-and-error through object emulation, but the community influenced the overall style and material choice. Once hafted, the shaft and ligatures would have covered most of the modifications (**Figure 4**), reducing the visibility of many production flaws on the shovel blade. The hafting arrangement could be adjusted until a shovel reached the desired visual effect.

Further, the lack of careful/high-quality production for an iconic object suggests two possibilities. First, the motivation for keeping this style tradition was primarily ideological and tied to group identity/membership. The scapulae likely mainly served as the armature to create a shovel that could display, conform or dazzle through the physical arrangement. Second, either the implement was not generally used for agricultural practices, or agriculture was not the primary source of subsistence. This last point is supported by previous studies on scapular shovel function (Xie et al., 2017), which found scapular implements to be ineffective in penetrating the ground, even in relatively soft soils. Furthermore, the absence of a training system for ensuring technical consistency and holding high product standards for shovel production suggests that farming activities were not a crucial component of the society's subsistence activities. This conclusion is consistent with the results of recent paleoethnobotanical research confirming low-level food production in the Hemudu's subsistence practice. Therefore, scapular shovels were likely a sign of group identity, emphasizing conformity to style, indicating that social conformity is not necessarily linked to specific learning patterns as ethnographic data may suggest.

CONCLUSION

Most Hemudu scapular spades were likely crafted by household craftspeople, who were adept and familiar with the implements but had insufficient training and practice, resulting in varying qualities of the tools and high variability of end-products. The pattern of self-sufficient household production combined with frequency-dependent bias led to a preference for bone spades and ensured their persistence in Hemudu Culture.

Communities of practice appear to have been minimal to nonexistent among the shovel makers; alternative mechanisms to maintain the technical norms of the scapular shovel tradition or hold a high product standard were also lacking. Therefore, the Hemudu community members developed their knowledge and skills of manufacture primarily through self-teaching and produced low to moderate quality shovel blades. This can be explained by the more profound subsistence background behind technological decision-making—the society did not rely on farming for survival.

This leaves us with ideology. Despite the variability in production, hafting style and material preference remain consistent. A bone shovel gains utility as a signal of group membership, where conformity lies in highly visible traits. This implies that farming activities might have been culturally significant despite minor economic contributions. The binary system of conformist hafting style and material preference mixed with loose quality control in the Hemudu scapular shovel blade production reveals that social conformity and the associated learning pattern are circumstantial and fluid even for a community's iconic implement.

The case study we presented here demonstrates how studying the learning patterns for osseous technology complements the lithic and pottery studies that dominate the technology literature. Further research with other bone artifact types in the Yangzi Delta would help shed light on whether similar learning patterns were applied besides the creation of scapular shovels and whether this type of implement was unique in its construction. If craft specialization existed in the bone industry of Neolithic Yangzi Delta, what were the causes of exception seen in shovels? Does the intention behind tool creation (e.g. foraging or plant cultivation) drive differences in craft learning? Additional study in this area will further our understanding of the socio-economic development of agriculture in the Yangzi Delta.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

LX conceptualized the project, collected and analyzed data, developed the methods, acquired funding, and took the lead in drafting the manuscript. CL participated in literature research and manuscript drafting. LJ and GS administrated the project and provided the archaeological resources.

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Stable Isotope Analysis of Mammalian Enamel From the Early Pleistocene Site of Madigou, Nihewan Basin: Implications for Reconstructing Hominin Paleoenvironmental Adaptations in North China

Zhe Xu[1,2,3], *Shuwen Pei*[1,2]*, *Yaowu Hu*[4], *Ignacio de la Torre*[5] *and Dongdong Ma*[1,2]

[1]*Key Laboratory of Vertebrate Evolution and Human Origins, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, China,* [2]*CAS Center for Excellence in Life and Paleoenvironment, Beijing, China,* [3]*School of Humanities, University of Chinese Academy of Sciences, Beijing, China,* [4]*Department of Cultural Heritage and Museology, Fudan University, Shanghai, China,* [5]*Department of Archaeology, Institute of History, CSIC- Spanish National Research Council, Madrid, Spain*

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Edited by:
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***Correspondence:**
Shuwen Pei
peishuwen@ivpp.ac.cn

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The reconstruction of environmental and climatic changes in the Pleistocene is an essential contribution to our understanding of human evolutionary and behavioral adaptations. Well preserved fluvio-lacustrine sediments at Nihewan basin have yielded a rich record of Early Pleistocene Paleolithic sites and mammalian fossils which provide a unique opportunity for exploring hominin behavior and paleoecology in North China. Taxonomic studies of mammalian fossils have provided important clues to the general environmental setting and landscapes of Early Pleistocene humans in the fluvio-lacustrine basin of Nihewan, but little is known about their isotopic signatures. In this paper, mammal teeth species at the Madigou archaeological site (ca. 1.2 Ma) were selected for bulk and sequential enamel stable isotope (C, O) analysis. Results show a variety of ecological environments, including grassland and sparse forest landscapes, and distinct patterns across taxa. C_3-C_4 mixed vegetation predominated, but C_4 vegetation was also relevant at times. Madigou early humans likely experienced cold/warm or dry/wet fluctuations in this northern China basin. We hypothesize that the environmental fluctuations and diversified landscapes may have driven flexibility in various aspects of early human technological behaviors, and allowed hominins to face the environmental challenges of northern latitudes after the initial expansion from Africa into East Asia at the onset of the Middle Pleistocene Climate Transition.

Keywords: stable isotopes, paleoenvironmental variability, Middle Pleistocene Climate Transition (MPT), human adaptations, Madigou site, Nihewan basin, North China

INTRODUCTION

Understanding the impact of paleoenvironmental variability on hominin behavioral adaptations is a key area of research in human evolution (deMenocal, 1995; Ambrose, 2001; Behrensmeyer, 2006), and is of crucial relevance for understanding the initial dispersal of humans from Africa into Eurasia (Gabunia et al., 2000; Bar-Yosef and Belfer-Cohen, 2001; Van der Made, 2011) and hominin

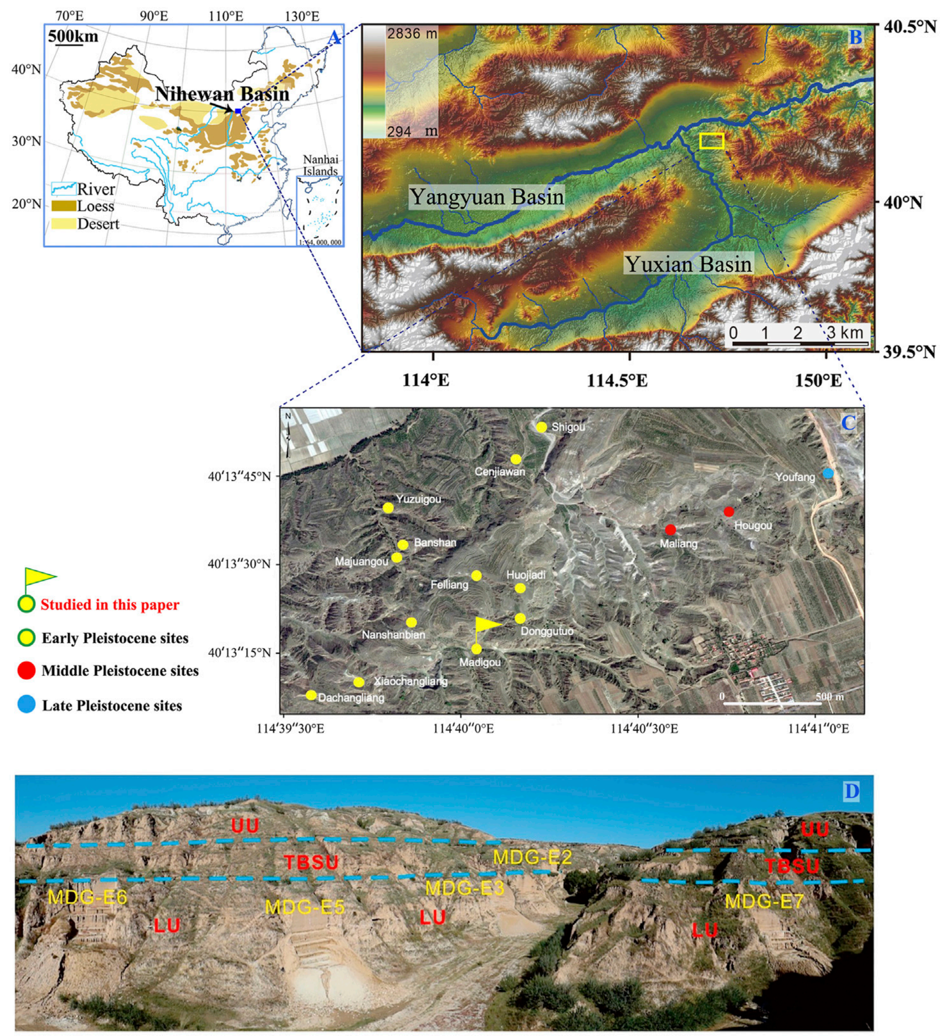

FIGURE 1 | (A–C) Location of the Nihewan Basin in China and the distribution of key Pleistocene sites in the Cenjiawan Platform. **(D)** Trenches at the MDG site complex, viewed from the southwest. Abbreviations: LU = lower unit. TBSU = thick brown sand unit. UU = upper unit (Pei et al., 2019).

behavioral adaptations during the Middle Pleistocene Climate Transition (MPT) at ~ 1.25–0.7 Ma, which is marked by a progressive increase in the amplitude of climate oscillations (Ruddiman et al., 1986; Mudelsee and Schulz, 1997; Clark et al., 2006; Wang et al., 2017). It has been hypothesized that the MPT triggered substantial hominin dispersals from Africa to Eurasia (Larick and Ciochon, 1996; Wu and Liu, 2001; Deng et al., 2007; Abbate and Sagri, 2012), and it may be linked to a more sustained settlement by *Homo erectus* in northern latitudes of East Asia. A more continuous occupation of northern latitudes would be aided by a diversity of adaptive behaviors, following patterns observed elsewhere (deMenocal, 2011; Grove, 2012; Potts, 2012, 2013; Potts and Faith, 2015), in which human biological evolution and lithic technological innovations were coupled with a high frequency of climatic fluctuation cycles.

The Nihewan Basin (**Figure 1**) in North China is well known for its abundance of archaeological sites through the Lower and Upper Pleistocene (Schick et al., 1991; Zhu et al., 2001, 2004; Deng et al., 2006, 2007; Ao et al., 2010, 2013; Zuo et al., 2011). Nihewan paleoenvironments have been reconstructed through the analysis of sedimentary features and mammalian enamel stable isotopes (Deng et al., 2001; An et al., 2005; Ding et al., 2005; Pei et al., 2009), pollen (Li et al., 1996; Wu et al., 2007; Pei et al., 2009), magnetic susceptibility (Deng et al., 2007; Pei et al., 2009, 2019), iron oxides (Pei et al., 2009), soluble salts (Li et al., 2010), and site formation processes (Jia et al., 2019). Recent archaeological studies (Pei et al., 2017, 2019; Yang et al., 2017, 2020, 2021) have discussed the links between climatic variability and human adaptations, suggesting that changes in lithic technological strategies occurred at the beginning of the MPT. Such changes would be evidenced by the flexibility in raw material procurement, diversification of flaking techniques, a refinement of retouching techniques, and an increase of tool types. However, the environmental context in which such new technological patterns emerged has not yet been properly ascertained.

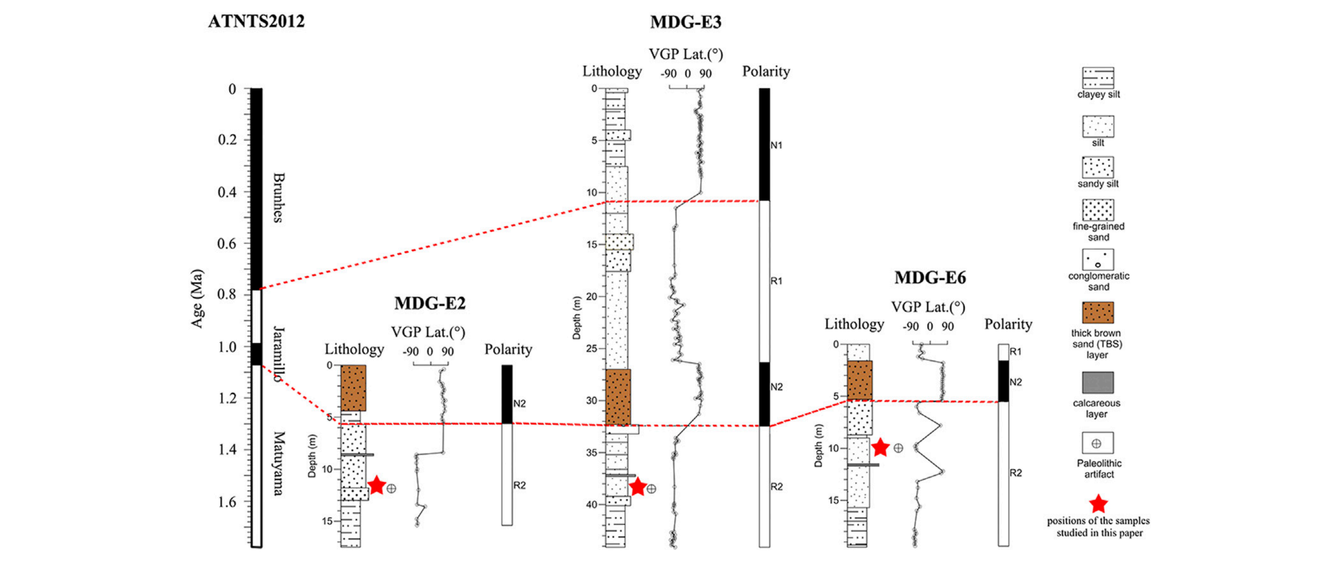

FIGURE 2 | Lithostratigraphy and magnetic stratigraphy of MDG-E2, MDG-E3 and MDG-E6, and positions of the samples studied (excluding one sample from MDG-E7) (Hilgen et al., 2012; Pei et al., 2019).

Stable isotope (C, O) analysis of tooth enamel provides direct evidence of the ecology and habitat of fossil mammals (Quade et al., 1992; Cerling et al., 1997; Cerling and Harris, 1999; Van der Merwe, 2013; Rivals et al., 2018; Uno et al., 2018), but is yet to be applied systematically to the Nihewan Pleistocene sequence. Here we contribute to this effort by presenting the first analysis of isotope values to mammalian teeth from the Madigou site (MDG). Our study includes bulk sampling from the whole teeth enamel and sequential sampling of several specimens, which were used to reconstruct paleolandscapes and seasonal variability in Early Pleistocene Nihewan, and to contextualize both with dynamics observed in the use of stone tools by early humans at the site.

TABLE 1 | Sampled teeth per taxa and trench at MDG.

Species	Location				Total
	E2	E3	E6	E7	
Muntiacus sp.	3	0	0	0	3
Cervidae gen. et sp. Indet	3	0	0	0	3
Moschidae gen. et sp. Indet	1	0	0	0	1
Bovidae gen. et sp. Indet	5	0	0	0	5
Other unidentifiable Cetartiodactyla	4	0	0	0	4
Coelodonta antiquitatis	22	6	1	0	29
Equus wangi sp. Nov.	9	1	0	0	10
Equus qingyangensis sp. Nov.	0	0	0	1	1
Other *Equus* sp.	11	1	0	0	12
Other unidentifiable ungulates	8	0	0	0	8
Canis chihliensis?	1	0	0	0	1
Total (*n*)	67	8	1	1	77

PRINCIPLES OF STABLE ISOTOPE (C, O) ANALYSIS OF FOSSIL ENAMEL

According to different pathways of photosynthesis, terrestrial plants are generally divided into three categories, C_3 (Calvin), C_4 (hatch slack) and CAM (Crassulacean acid metabolic acid), which cause the differences of carbon isotopic fractionation during the processes of carbon fixation. $\delta^{13}C$ values of C_3 plants, including trees, shrubs and cold-tolerant herbs (Deng et al., 2001), range from −34‰ to −22‰, while those of C_4 plants, typical of drier and warmer environments (Raven et al., 1999), range from −17‰ to −9‰ (O'Leary, 1988; Farquhar et al., 1989; Cerling et al., 1997). Other factors such as rainfall, altitude, light intensity, atmospheric carbon dioxide concentration and the canopy effect also affect the $\delta^{13}C$ values of plants (Farquhar et al., 1989). $\delta^{13}C$ values of C_3 plants become more negative with the increase of the rainfall, altitude and latitude (Kohn, 2010). Isotopic fractionation takes place from diets to teeth enamel when plants are eaten by herbivores, and when herbivores are consumed by carnivores. Compared to those in plants, $\delta^{13}C$ values of teeth enamel from large herbivores and carnivores increase by ~14‰ and ~9‰ respectively (Cerling and Harris, 1999; Tejada-Lara et al., 2018). Following earlier work (Cerling et al., 1997; Wang et al., 2008; Biasatti et al., 2010; Uno et al., 2018), the $\delta^{13}C$ values in tooth enamel lower than -8‰ are attributed in this study to animals that only eat C_3 food, from -8‰ to −2‰ to those with a C_3-C_4 mixed diet, and higher than −2‰ to those consuming mainly C_4 foods.

The oxygen isotope composition in mammalian teeth is mainly determined by that of body water, which derives directly from drinking water (Pederzani and Britton, 2019). Due to evaporation, $\delta^{18}O$ values in plant leaves are higher than those in meteoric water. This results in leaf-eating herbivores having higher $\delta^{18}O$ values than those drinking meteoric water (Pederzani and Britton, 2019), thus enabling to distinguish browsers from grazers. Additionally, $\delta^{18}O$ values vary with the altitude, temperature and latitude, which helps to track

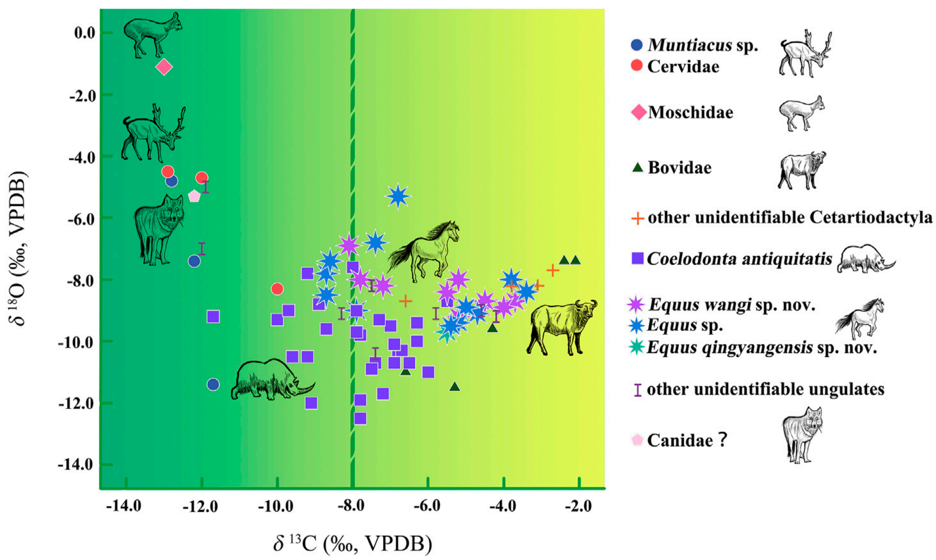

FIGURE 3 | $\delta^{13}C$ and $\delta^{18}C$ values of the MDG teeth assemblage.

animal movement across different ecozones (Pederzani and Britton, 2019).

Two sampling strategies are usually applied to the isotopic analysis of fossil teeth enamel. Bulk sampling of the whole enamel is used to reconstruct the average diet and ecological setting during the period of tooth formation (Feranec and MacFadden, 2000). Sequential sampling of the enamel along the direction of enamel growth may reveal the spatiotemporal dietary and environmental changes throughout the development of the tooth (Balasse, 2002).

MATERIAL AND METHODS

Geological Setting of the Madigou Site

The Nihewan Basin (which includes the Yangyuan Basin and Yuxian Basin in Hebei Province, and the Datong Basin in Shanxi Province), is an intermontane basin between the Inner Mongolian Plateau and North China (Deng et al., 2019; Pei et al., 2019) (**Figure 1A**). It is well known for its extensive late Cenozoic fluvio-lacustrine sequence (the Nihewan Beds), reliably-constrained geochronology, and abundant archaeological sites (Schick et al., 1991; Zhu et al., 2001, 2004; Deng et al., 2006, 2007; Ao et al., 2010, 2013; Zuo et al., 2011). (**Figures 1A–C**). The Nihewan Beds contain fluvio-lacustrine deposits from the Late Pliocene to the late Middle/Upper Pleistocene (Zhao et al., 2010; Nian et al., 2013; Deng et al., 2019). These deposits include the Pliocene-Pleistocene boundary (Liu et al., 2012) and the Nihewan faunas (*sensu lato*) (Teilhard de Chardin and Piveteau, 1930; Zhou et al., 1991; Qiu and Qiu, 1995), and are constrained at the bottom by the Pliocene red clay and overlain by the Late Pleistocene Malan loess (Deng et al., 2019) at the top of the sequence. Current geochronological and archaeological research show that early hominins may have continuously occupied the Nihewan Basin from 1.66 Ma (Zhu et al., 2004) to the Late Pleistocene (Schick et al., 1991; Zhu et al., 2001, 2004; Pei et al., 2019).

Madigou (40°13′07–16″N, 114°39′58″–40′18″E) is located in the northwest margin of the Cenjiawan platform (eastern part of the Nihewan Basin). Paleomagnetism indicates that the MDG stratigraphy comprises the early Brunhes normal chron and the late Matuyama reverse chron, including the Jaramillo normal subchron (**Figure 2**). The MDG archaeological layers are positioned within the pre-Jaramillo Matuyama chron, with an estimated age of ca. 1.2 Ma, i.e., chronologically within the onset of the MPT. Stratigraphic correlations of seven trenches excavated at MDG indicate that the MDG chronostratigraphic sequence begins with MDG-E2, followed by MDG-E3, MDG-E5 and MDG-E7, and contains the most recent units at MDG-E6 (**Figure 1D**) (Pei et al., 2019). A total of 1,517 lithic artifacts and over 900 fossil remains, including *Equus*, *Coelodonta antiquitatis*, Cervidae, Bovidae, and others, were unearthed from the lower part of the sequence in each trench, especially in MDG-E2 and MDG-E3 (Pei et al., 2019). Predominance of ungulates in the fossil assemblage suggested open grasslands and a sparse steppe (Pei et al., 2019).

Chert dominates among lithic raw materials, followed by siliceous dolomite (Pei et al., 2019). MDG knappers showed a preference for specific rock types, such as siliceous dolomite cobble for bipolar knapping, brecciated chert blocks for freehand hard hammer flaking, and high-quality chert for retouching tools (Pei et al., 2019).

The MDG fossils were spatially associated with stone artifacts, and preliminary zooarchaeological results suggest human action over part of the fossil assemblage (Pei et al., 2019). Thus, the ecological and environmental data retrieved from the isotopic

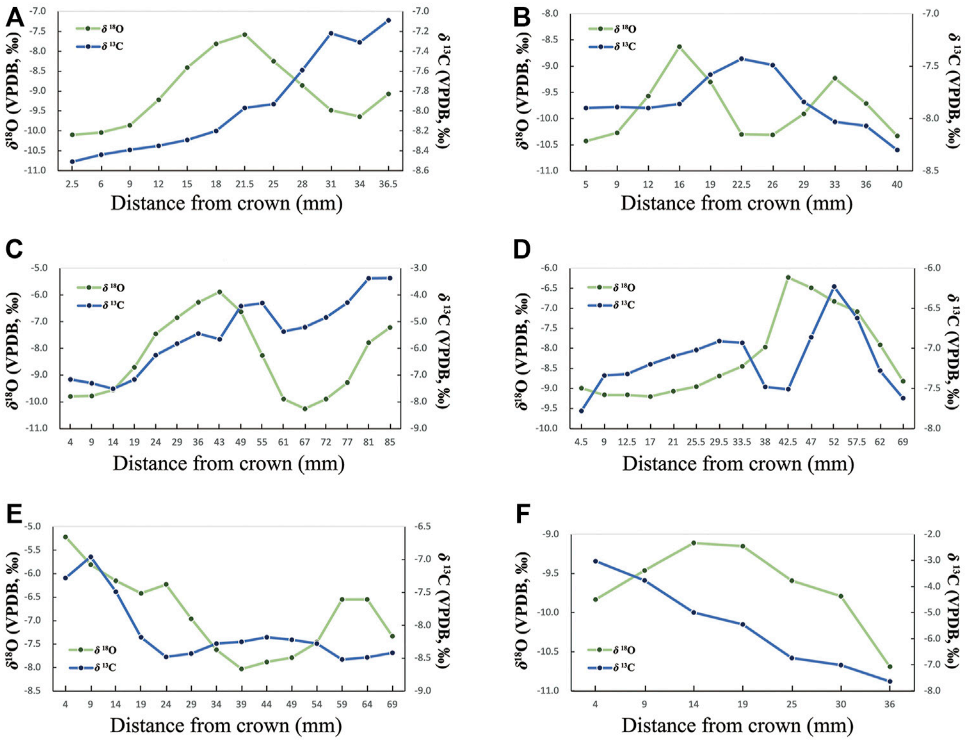

FIGURE 4 | Sequential isotopic profiles from MDG teeth **(A)**. MDG10: *Coelodonta antiquitatis*, Frag; **(B)**. MDG11: *Coelodonta antiquitatis,* M3; **(C)**. MDG16: *Equus wangi* sp. Nov., m3; **(D)**. MDG19: *Equus wangi* sp. Nov., P4; **(E)**. MDG22: *Equus wangi* sp. Nov., P4; **(F)**. MDG23: *Equus qingyangensis* sp. Nov., p4).

TABLE 2 | Serial sampling data of MDG teeth.

Taxa	Lab code	n	δ^{13}C (‰)				δ^{18}O (‰)			
			Median	SD	Max	Min	Median	SD	Max	Min
Coelodonta antiquitatis	MDG10	12	−7.9	0.5	−7.1	−8.5	−9.0	0.9	−7.6	−10.1
	MDG11	11	−7.8	0.3	−7.4	−8.3	−9.8	0.6	−8.6	−10.4
Equus wangi sp. Nov.	MDG16	16	−5.5	1.3	−3.4	−7.5	−8.4	1.5	−5.9	−10.3
	MDG19	15	−7.2	0.4	−6.2	−7.8	−8.2	1.1	−6.2	−9.2
	MDG22	14	−8.1	0.5	−7.0	−8.5	−6.9	0.9	−5.2	−8.0
Equus qingyangensis sp. Nov.	MDG23	7	−5.5	1.7	−3.0	−7.6	−9.7	0.5	−9.1	−10.7

analysis of fossil enamel presented herein also informs on the landscapes occupied by early humans at Nihewan.

Sample Selection

Seventy-seven fossil teeth from archaeological layers at MDG were selected for isotopic analysis: 67 from trench MDG-E2, 8 from trench MDG-E3, and one from each MDG-E6, and MDG-E7 (**Figure 2**). Bulk sampling was made from 71 teeth of Cervidae (*Muntiacus* sp.), Moschidae, Bovidae, Rhinocerotidae (*Coelodonta antiquitatis*), Equidae (*Equus wangi* sp. Nov. and *Equus qingyangensis* sp. Nov.), Canidae (*Canis chihliensis*?) and others (**Table 1**; **Supplementary Table S1**).

Six additional teeth were serially sampled: 2 of *Coelodonta antiquitatis*, 3 of *Equus wangi* sp. Nov., and 1 of *Equus qingyangensis* sp. Nov. (see details in **Supplementary Tables S2–7**). No first molars were included, to prevent the breastfeeding effect on isotopic data.

Sample Preparation and Isotopic Measurements

Bioapatite pretreatment was undertaken at the Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences (IVPP), and followed the protocols described in Lee-Thorp et al. (1989), Bocherens et al. (1994), Koch et al. (1997), and Wright and Schwarcz (1999). Before sampling, any contaminations on the enamel surface were removed with a dental drill. For the 71 teeth selected for bulk sampling, 15–30 mg enamel powder were extracted evenly from different parts of the enamel and grinded to below 200 meshes with agate mortar. Sequential samples of six additional teeth were

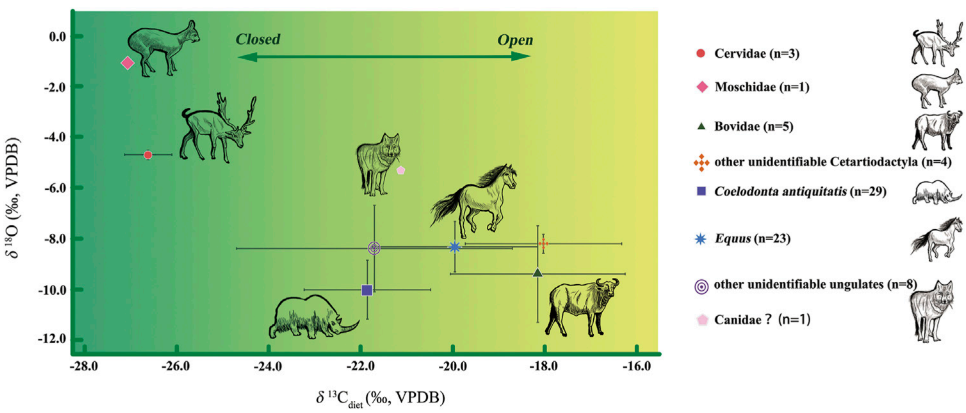

FIGURE 5 | Niche reconstruction of the MDG fossil assemblage, based on $\delta^{13}C_{\text{diets}}$ and $\delta^{18}O_{\text{enamel}}$ values.

collected from crown to neck along the enamel growth axis. The average sampling interval was 5 mm, and 15–20 mg of each sample was collected.

To remove the organic matter, about 1.5 ml of 2.5% sodium hypochlorite was added into the 2.0 ml tubes for each sample. After full reaction, samples were centrifuged and washed to neutrality with distilled water. Subsequently, 1.5 ml of 1 M acetic acid was added for 20 h to each sample to remove the secondary carbonate. Samples were subsequently cleaned with distilled water, freeze-dried and ground into powder again.

Isotopic measurements were undertaken in an Isotope Ratio Mass spectrometer (MAT-253) combined with a Gas bench system in the Laboratory for Stable Isotope Geochemistry, Institute of Geology and Geophysics, Chinese Academy of Sciences. The isotopic results were expressed as $\delta^{13}C$ and $\delta^{18}O$, relative to the VPDB. The isotopic standards used for isotopic calibration were NBS 18, NBS 19 and GBW04405 ($\delta^{13}C_{VPDB}$ = 0.57 ± 0.03‰, $\delta^{18}O_{VPDB}$ = −8.49 ± 0.14‰; Certified reference material approved by the State Bureau of Technical Supervision, the People's Republic of China). The precisions of $\delta^{13}C$ and $\delta^{18}O$ values are better than 0.15‰ and 0.20‰ respectively. Isotopic data are listed in **Supplementary Tables S1–7**.

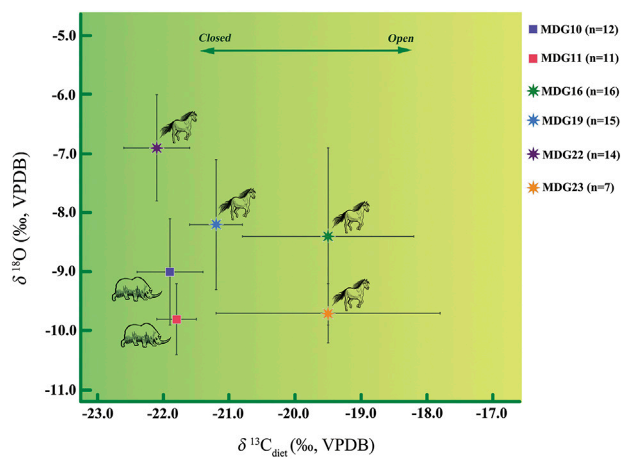

FIGURE 6 | Reconstructed $\delta^{13}C_{\text{diets}}$ and $\delta^{18}O_{\text{enamel}}$ values from sequential samples of MDG teeth. MDG10 and MDG11: *Coelodonta antiquitatis*. MDG16, 19 and 22: *Equus wangi* sp. Nov. MDG23: *Equus qingyangensis* sp. Nov.

RESULTS

Isotopic Analysis of Bulk Samples

Figure 3 shows large isotopic variations among specimens that suggest different niches. The $\delta^{13}C$ values range from −13.0‰ to −2.1‰ and average −7.3 ± 2.7‰ (n = 77), while the $\delta^{18}O$ values range from −12.5‰ to −1.1‰ and average −8.8 ± 1.9‰ (n = 77).

Artiodactyls

The $\delta^{13}C$ value of Moschidae (n = 1) is −13.0‰, indicating a closed C_3 environment. This sample shows the highest $\delta^{18}O$ value (−1.1‰).

Cervidae (n = 6) includes *Muntiacus* sp. and other unidentifiable Cervidae taxa. Their $\delta^{13}C$ values range from−12.9‰ to −10.0‰, with a mean of −12.0 ± 1.1‰. $\delta^{18}O$ values range between −11.4‰ and −4.5‰, averaging −6.9 ± 2.7‰ (n = 6). However, given the abnormally low $\delta^{18}O$ values of MDG13 (−8.3‰), MDG55 (−7.4‰) and MDG57 (−11.4‰), which might be due to the fact that the individuals come from other regions, the isotope data from those teeth are excluded from the following statistical analysis and discussion. The mean values of $\delta^{13}C$ and $\delta^{18}O$ in remaining Cervidae (n = 3) are −12.6 ± 0.5‰ and −4.7 ± 0.1‰ respectively, which indicates that MDG Cervidae fed in a pure C_3 environment.

Bovidae (n = 5) show $\delta^{13}C$ values from −6.6‰ to −2.1‰, averaging −4.2 ± 1.9‰ and $\delta^{18}O$ values from −11.5‰ to −7.4‰ (average of −9.4 ± 1.9‰). This suggests that they consumed mixed C_3-C_4 plants. It is notable that one specimen (MDG61) has the highest $\delta^{13}C$ value (−2.1‰) among the entire assemblage, indicating a nearly neat C_4 environment.

Perissodactyls

The δ^{13}C values of *Coelodonta antiquitatis* (n = 29) differ from those of carnivores and artiodactyls, ranging from −11.7‰ to -5.5‰ (mean = −7.9 ± 1.4‰). This indicates that the habitat of *Coelodonta antiquitatis* ranged between closed forest and open grassland landscapes. MDG *Coelodonta* teeth yield the lowest average δ^{18}O value [−10.0 ± 1.2‰, (n = 29)] in the entire assemblage, which could be related to consumption of meteoric water.

The δ^{13}C values of *Equus* (n = 23) range from −8.7‰ to −3.4‰ (average of −6.0 ± 1.8‰) and their δ^{18}O values range from −9.7‰ to -5.3‰ (mean = −8.3 ± 1.0‰). This indicates their preference for more open environments compared to *Coelodonta antiquitatis*.

Carnivores

The δ^{13}C value of a sole specimen of Canidae is −12.2‰. Its δ^{18}O value is −5.3‰, higher than those from *Coelodonta*, *Equus*, and Bovidae.

Isotopic Analysis of Sequential Samples

The δ^{13}C profiles from sequential samples of *Coelodonta antiquitatis*, *Equus wangi* sp. Nov., and *Equus qingyangensis* sp. Nov., suggest considerable variations of the diet throughout the life history of these specimens. Pure C_3 or nearly pure C_4 vegetation predominated occasionally, but C_3-C_4 mixed vegetation dominated. Variations observed in δ^{13}C profiles could indicate an oscillation between dry and wet seasons, while variability in δ^{18}O profiles may indicate periodic or seasonal fluctuations in precipitation (**Figure 4**; **Table 2**).

DISCUSSION

Niche Reconstruction in the Nihewan Basin at the Beginning of the MPT

Considering the fractionation of carbon isotope from diet to enamel bioapatite (with an enrichment of 14‰ in large herbivorous and of 9‰ in carnivores) (Tieszen et al., 1983; Cerling and Harris, 1999; Tejada-Lara et al., 2018), the niches of the MDG fauna can be reconstructed on the basis of isotopic data from bulk samples (**Figure 5**). We conclude that the fauna accumulated at the MDG site occupied a relatively broad niche, from open grassland to closed forest.

In terms of $\delta^{13}C_{diets}$ values, Moschidae and Cervidae have the highest negative $\delta^{13}C_{diets}$ values, indicative of a closed forest. On the other end, *Equus* and Bovidae have the most positive $\delta^{13}C_{diets}$ values, typical of open environments. The large standard deviations in Bovidae ($\delta^{13}C_{diets}$: 1.9‰) and *Equus* ($\delta^{13}C_{diets}$: 1.8‰) suggest that they had a more flexible dietary breadth. Conversely, the smaller standard deviations in *Coelodonta antiquitatis* ($\delta^{13}C_{diets}$: 1.4‰) may indicate a more specialized diet.

Regarding $\delta^{18}O_{enamel}$ values, **Figure 4** shows that Moschidae (−1.1‰) and Cervidae (−4.7 ± 0.1‰) have more positive average $\delta^{18}O_{enamel}$ values than *Equus* (−8.3 ± 1.0‰), Bovidae (−9.4 ± 1.9‰) and *Coelodonta antiquitatis* (−10.0 ± 1.2‰). This indicates a preference in Moschidae and Cervidae for more ^{18}O-enriched foods (such as leaves). Overall, the standard deviation in *Coelodonta antiquitatis* ($\delta^{13}C_{diets}$: 1.4‰, $\delta^{18}O_{enamel}$: 1.2‰) suggests more limited foraging flexibility, habitat and narrower ecological adaptability than *Equus* ($\delta^{13}C_{diets}$: 1.8‰, $\delta^{18}O_{enamel}$: 1.0‰) and Bovidae ($\delta^{13}C_{diets}$: 1.9‰, $\delta^{18}O_{enamel}$: 1.9‰).

As shown in **Figure 6**, the isotopic profiles from *Coelodonta antiquitatis* and *Equus* indicate seasonal changes. MDG23 (*Equus qingyangensis* sp. Nov.) ($\delta^{13}C_{diets}$: 1.7‰) and MDG16 (*Equus wangi* sp. Nov.) ($\delta^{13}C_{diets}$: 1.4‰) have the largest variation in the $\delta^{13}C_{diets}$ standard deviation, which suggests their adaptability to varied landscapes in nearly pure C_4, mixed C_3-C_4 and nearly pure C_3 vegetation. In contrast, the low standard deviation in MDG11 (*Coelodonta antiquitatis*) ($\delta^{13}C_{diets}$: 0.3‰) indicates a relatively fixed niche and narrow ecological adaptability for this individual. On the other hand, standard deviations of MDG16 ($\delta^{18}O_{enamel}$: 1.5‰), MDG19 (*Equus wangi* sp. Nov.) ($\delta^{18}O_{enamel}$: 1.1‰), MDG10 (*Coelodonta antiquitatis*) ($\delta^{18}O_{enamel}$: 0.9‰) and MDG22 (*Equus wangi* sp. Nov.) ($\delta^{18}O_{enamel}$: 0.9‰) are large, which reflects a seasonal variation of regional temperature and precipitation.

Changing Landscapes and Human Behavioral Adaptations in the Nihewan Basin at the Onset of the MPT

It has been proposed that human occupation of the Nihewan Basin during the Early Pleistocene was discontinuous and that the area would only be populated during interstadial periods and in the warm seasons (Dennell, 2003, 2013). While systematic testing is still needed through multiple proxies and across the archaeological sequence (de la Torre et al., 2020), our contribution on the isotopic analysis of the MDG faunal assemblages does not seem to support such hypothesis. Variability of patterns in δ^{18}O and δ^{13}C values (**Figure 4**) strongly suggests input of mammal carcasses to the site during various seasons. In addition, considering other archaeological evidence in the Nihewan Basin, it has been suggested that Early Pleistocene humans in North China could have adopted flexible technological strategies as a response to environmental fluctuations (Pei et al., 2019).

In the case of MDG, early humans preferentially used preferentially siliceous dolomite cobbles in the bipolar technique, breccia chert blocks for freehand hard-hammer percussion, and selected high-quality chert for retouching tools (Pei et al., 2017, 2019). This suggests a structured procurement of raw materials based on the technological requirements of each knapping activity.

CONCLUSION

Mammal fossils unearthed in archaeological sites play an important role in assessing the impact of environmental instability in human behavioral adaptations. This paper analyzed stable isotope ratios of fossil tooth enamel at the recently discovered Early Pleistocene site of MDG, in the Nihewan Basin. Isotopic data from bulk teeth enamel shows that the MDG fauna occupied a wide niche, including pure C_3, C_3-C_4 mixed, and nearly pure C_4 environments. The $\delta^{13}C$ and $\delta^{18}O$ profiles of tooth sections indicate substantial regional dry/cold and warm/wet fluctuations and seasonal variations.

Most likely, changing environments had an impact on human behavioral adaptations archaeologically detectable through stone tool technological variability. Previous studies (Pei et al., 2019) have discussed the technological plasticity of MDG hominins in raw material procurement strategies, knapping techniques, tool preferences and lithic reduction sequences, all of which might potentially be linked to environmental fluctuations such as those reported in this study. Further studies should explore other paleoenvironmental proxies and their application to other archaeological assemblages at the Nihewan Basin, in order to test how early humans coped with the instability characteristic of the MPT, and to portrait more accurately dynamics of hominin occupation in north China during this period.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

ZX: Investigation, analysis, writing, and original draft preparation. SP: Investigation, designed the research and writing. YH: Academic support and writing. IdlT: Writing. DM: Investigation and analysis. All authors have contributed to the article and approved the submitted version.

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Evidence of Fire Use by *Homo erectus pekinensis*: An XRD Study of Archaeological Bones From Zhoukoudian Locality 1, China

*Chao Huang[1,2,3], Jingshu Li[1,2] and Xing Gao[1,2,3]**

[1]Key Laboratory of Vertebrate Evolution and Human Origins, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, China, [2]CAS Center for Excellence in Life and Paleoenvironment, Beijing, China, [3]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, China

Zhoukoudian Locality 1 is well known both for the discovery of *Homo erectus* fossils and for the presence of early evidence of controlled use of fire by hominins; However, the nature of the latter had been seriously questioned since mid-1980s. To obtain substantial evidence of fire use by hominins, we combine macroscopic observations and XRD analysis on 23 fossil bones from new excavations in Layers 4 and 5. The crystalline index shows that at least 15 fossil bones were heated above 600°C, and this is partly consistent with macroscopic observations. The high intensity burning of bones may indicate strong evidence of hominin-controlled use of fire at Layer 4. Future work should focus on archaeological materials from lower layers to improve our understanding of the nature of colored bones and gain more solid evidence of fire use by early humans at Zhoukoudian.

Keywords: Pleistocene, Zhoukoudian locality 1, *Homo erectus pekinensis*, burned bone, crystalline, use of fire, zooarchaeology

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****Correspondence:***
Xing Gao
gaoxing@ivpp.ac.cn

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INTRODUCTION

Zhoukoudian Locality 1, situated about 50 km southwest of Beijing, China, (**Figure 1**), has been well known since the 1920s for the discovery of a large number of *Homo erectus pekinensis* fossils and thousands of stone artifacts. In addition, some burned items were also uncovered from the site, such as charcoal, stones and bones and they were widely accepted as the oldest reliable evidence of hominin use and maintenance of fire in the world (Black, 1931; Pei, 1934). From 1980s to the beginning of this century, based on information derived from taphonomy, geochemistry and spatial analysis, scholars have begun to doubt the evidence of *in situ* burning at the site and further the notion that *Homo erectus pekinensis* had the ability to control fire (Binford et al., 1985; Binford et al., 1986; Weiner et al., 1998; Goldberg et al., 2001; Boaz et al., 2004). Researchers from China refuted these arguments from perspectives of elemental carbon concentration and taphonomic observations (Wu, 1999; Shen, 2004).

In a recent excavation campaign conducted at Zhoukoudian Locality 1 since 2009, burned sediments and roughly one hundred of burned bones have again been unearthed from the site (Gao et al., 2016; Gao et al., 2017). By analyzing soil samples sourced during the new excavations in Layer 4, Zhong et al. (2013) detected siliceous aggregates which provided compelling evidence of the *in situ* use of fire by hominins at the site. Zhang et al. (2014) analyzed the sediment from the same Layer by

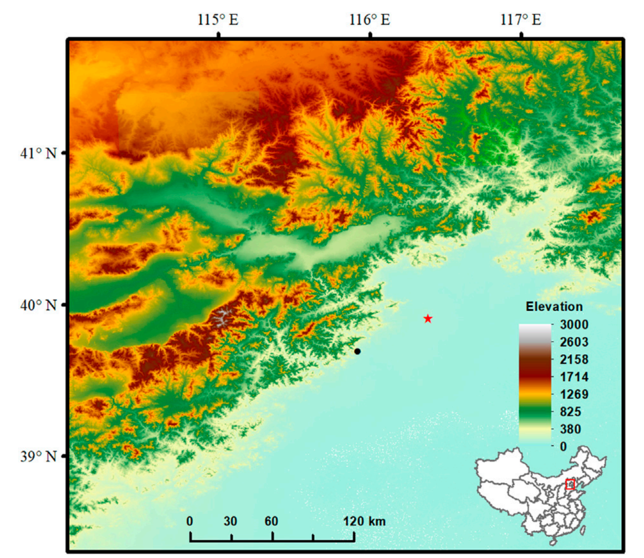

FIGURE 1 | The location of Zhoukoudian Loc.1.

examining its magnetic susceptibility, diffuse reflectance spectrum and color and presented further evidence of human controlled use of fire rather than a natural fire at the site.

However, it seems clear that these recent studies were focused essentially on sedimentary samples sourced from Layer 4, which represents in essence a single source of fire use at the site. In this study, we will pursue a different avenue and conduct an analysis of the newly excavated burned bones from the site.

In Paleolithic sites, burned bones are mostly used as an evidence of hominin use of fire (Black, 1931; Oakley, 1956; Brain & Sillen, 1988; Brain, 1993; Sillen & Hoering, 1993; Roebroeks & Villa, 2011; Gao et al., 2017; Hlubik et al., 2017). The presence of burned bones in an archaeological site might indicate a series of human activities such as meat processing (Brain, 1993; Wrangham & Conklin-Brittain, 2003), bone disposal (Yravedra & Uzquiano, 2013), hearth making (Bennett, 1999) and fuel management (Théry-Parisot, 2002).

A common practice employed by taphonomists during the past decades to differentiate the burned and unburned bone and further to estimate the intensity of burning is actually based on the color and/or texture of the bones from the archaeological sites (Baby, 1954; Wells, 1960). However, it has become clear now that color is a poor criterion in recognizing burned bones and estimating the intensity of burning (Oakley, 1961; Herrmann, 1977; Brain & Sillen, 1988; Brain, 1993; Sillen & Hoering, 1993; Taylor et al., 1995; Shahack-Gross et al., 1997; Thompson, 2004; Squires et al., 2011).

There are numerous researches that focus on analyzing the processes undergone by bones and sediments in archaeological or paleontological sites. In many of those researches, it is common to find that thermal events affected both bones and sediments (Weiner et al., 1993; Person et al., 1995; Stiner et al., 1995; Schiegl et al., 1996; Stiner et al., 2001; Monge et al., 2014). However, the recognition of burned bones from archaeological sites is not straightforward. A dark color on the bones may indicate a result of burning, but it could be due to staining by iron oxides or/and manganese. This situation has led to a lot of experimental studies of identifying burned bones and the intensity of their burning (Shipman et al., 1984; Buikstra & Swegle, 1989; Nicholson, 1993; Stiner et al., 1995; Schiegl et al., 1996; Bennet, 1999; Stiner et al., 2001; Lebon et al., 2008; Lebon et al., 2010; Reidsma et al., 2016; Schmahl et al., 2017; Greiner et al., 2019; Hoesel et al., 2019). These studies have concluded that thermal events could lead to a series of changes in color, texture, mineral phase, crystallinity, and modification of mechanical properties. In our study, we intend to combine XRD (X-Ray Diffraction) techniques and macroscopic observation to identify burned bones and estimate the intensity of their burning at Zhoukoudian Loc.1, and we hope this study will support evidence of hominin maintenance and use of fire at the site.

MATERIALS AND METHODS

From Layers 4 and 5, based on the state of preservation and thermal effects, we took a total of 23 samples of fossil bone. The fossils we used in this study were from the re-excavation of the Peking Man site at Zhoukoudian Locality 1.

The chronology of the use of fire by *Homo erectus pekinensis* was studied in 1991 using fission-track dating to find that the ash present at Locality 1 was likely deposited 299 ± 55 ka (Layer 4; Guo et al., 1991). Thermoluminescence dating was also applied at this site, generating an age of 292–312 ka for Layer 4 (Pei, 1985). Shen et al. (2001) using mass spectrometric U-series dating of intercalated calcite samples from the sediments at the site, proposed a date of 400 ± 8 kyr ago for an upper horizon of Layer 1/2 and ~500 kyr ago for the upper part of Layer 5. Thus, a range of 400–500 ka could be reasonably estimated for Layer 4, which was stratigraphically situated in-between these strata. It is notable that the dates for Layer 4 proposed by Guo et al. (1991), Pei, (1985) are far different from the estimates we obtained for the same layer by interpolating of the dating sets reported by Shen et al. (2001). Nonetheless, it has been argued that mass spectrometric U-series dating of pure calcite samples is a more reliable chronometer (Ludwig and Renne, 2000; Richards and Dorvale, 2003); this argument seems reinforced by an independent check conducted at Zhoukoudian recently (Shen et al., 2009). In this paper, we choose to use the older age for Layer 4 as indicated in the work of Shen et al. (2001).

Macroscopic Observation

We photographed all fossil bones and collected data on features including surface modifications. The bone surfaces were first examined by naked eye under strong incandescent light; potential marks of interest were then scrutinized using a 40× hand-lens and a Wild Heerbrugg microscope. Macroscopic characteristics (color and texture) of burned bones were identified following measures described by Stiner et al. (1995), Nicholson (1993), Buikstra and Swegle (1989).

Color is most commonly used to identify burned bone and the intensity of heat that the bone reached. The color code

TABLE 1 | Burn color code and descriptions by criteria.

Code	Color	Description
0	Unburned white	Not burned Off-white/cream/tan
1	Brown or red	Slightly burned Localized and <50% black
2	Dark brown	Lightly burned >50% black
3	Black	Fully carbonized Completely black
4	Gray	Localized <50% calcine White appears but < black
5	Light Gray	>50% calcined White > black
6	White	Fully calcined Completely white

described in the Munsell soil color chart (Munsell Color Company, 1954) was used with a seven-grade scale (0–6) as described by Stiner et al. (1995), based on amount of carbonization and calcination and incorporating the colors described by Nicholson (1993). The revised criteria we used in recording color are listed in **Table 1**.

Texture changes were taken together with color to help corroborate the extent of burning. Overall texture of burned bones was recorded following Nicholson, (1993) four-stage description; a standard light microscope was sufficient for the texture observations. **Table 2** shows the code we used in describing bone textures.

XRD Analysis

In early studies, many scholars mentioned that it could be determined whether skeletal remains had been burned, and the maximum temperature they reached, by matching their X-ray diffraction patterns (Shipman et al., 1984; Holden et al., 1995; Rogers and Daniels, 2002; Etok et al., 2007; Lebon et al., 2010; Greiner et al., 2019; Hoesel et al., 2019). All pointed out a phenomenon by which the XRD pattern of burned bone would become sharper when heated to 550°C or 600°C or above, although diagenesis and low-temperature heating may cause similar phenomena in bone mineral change. In our previous study, we saw a similar phenomenon in three distinct types of experimental burned bone (Huang and Zhang, 2021).

To identify mineral phases and crystallinity, we ground all bone fossils to a fine powder using an agate mortar. It is noted that samples of two colors were taken from different parts in the cases of NO.12Z1-862 and NO.12Z1-2103 (**Figure 2**). The colors of powdered samples were recorded by reference to the Munsell soil color chart (Munsell Color Company, 1954).

X-ray diffraction (XRD) patterns were recorded using a Bruker D8 Advance diffractometer. We used a copper target X-ray tube, operating at 40 kV and 40 mA. We collected measurements in the 3°–70° 2θ range, with a step size of 0.02° 2θ and a scan rate of 4°/min. From the XRD patterns, crystallinity index (CI) values of hydroxyapatite $[Ca_{10}(PO_4)_6(OH)_2]$ were determined following the methodology proposed by Landi et al. (2000). The crystallinity degree, corresponding to the fraction of

FIGURE 2 | Appearance of distinct colors in 12Z1-862 and 12Z1-2103.

TABLE 2 | Burned bone textures and criteria.

Texture code	Description
1	Unburned appearance without any burning fracture
2	Glass-like or bubbly char; curved, tiny fractures; clinker remains
3	Little to no char, flat granular surface, little or extensive cracking
4	Smoother surfaces, some warping

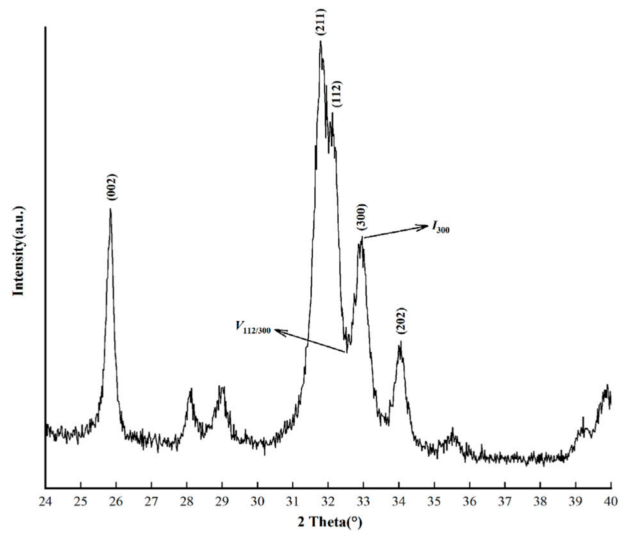

FIGURE 3 | Diffraction pattern of powder hydroxyapatite with 99% purity.

crystalline phase present in the examined volume, was evaluated using the relation

$$X_c \approx 1 - \left(\frac{V_{112/300}}{I_{300}}\right)$$

where I_{300} is the intensity of (300) reflection. Meanwhile, $V_{112/300}$ is the intensity of the hollow between (300) and (112) reflection, which completely disappears in non-crystalline samples (**Figure 3**).

Person et al. (1995), Stiner et al. (2001) pointed out that there was no correlation between increase in CI and age of fossil bone samples.

RESULTS

Table 3 shows results from macroscopic observation and XRD analysis. All samples were from Layer 4 except the Layer-5 sample 15Z1-0247. From the results we could see that the color codes ranged from 0 to 5, and the powder colors described using the Munsell color chart showed more refined color descriptions. Texture codes ranged from 1 to 4; it seemed that cracks were not clear in some specimens, and we did not find any traces of clinker, meaning the bones were not burned green (Cain, 2005). The CI values ranged from 0.15 to 0.84, mostly >0.3. In addition to hydroxyapatite, we also observed calcite and quartz in mineral composition, which implied diagenesis. We did not find traces of tooth marks.

Bone Description

As **Figures 4**, **5** show, we followed Nicholson (1993), Stiner et al. (1995) in choosing distinct colors of fossil bone to represent different burning intensities.

There was no fully calcined (i.e., completely white) bone among these samples, hence color code 6 was not used. However, in sample 15Z1-0247, the color of bone itself was hard to distinguish from the color in bones that showed a high intensity of burning (see **Figure 5**). The Munsell color code of powder in 15Z1-0247 was N 9/, making it the whitest sample. However, after reviewing the texture of the sample, we

TABLE 3 | Results from macroscopic observation and XRD analysis.

ID	Color code	Munsell color code	Texture	CI	Phase
15Z1-0247	0	N9/White	1	0.15	HAP
12Z1-1873	1	10YR8/2 Very pale brown	1	0.30	HAP Calcite Quartz
12Z1-1899	1	10YR8/3 Very pale brown	1	0.25	HAP
12Z1-1526	1	10YR8/3 Very pale brown	1	0.20	HAP Calcite Quartz
14Z1-0299	2	10YR5/1 Gray	2	0.17	HAP
14Z1-0273	4	N8/White	3	0.44	HAP
14Z1-0461	5	N8/White	3	0.52	HAP
14Z1-0143	4	10YR7/1 Light gray	3	0.42	HAP
14Z1-429	3	10YR5/2 Grayish brown	3	0.43	HAP
14Z1-0163	5	10YR7/1 Light gray	3	0.39	HAP Calcite Quartz
14Z1-1665	2	10YR7/2 Light gray	3	0.28	HAP
14Z1-1548	3	10YR4/1 Dark gray	4	0.39	HAP
12Z1-1510	4	10YR5/2 Grayish brown	2	0.52	HAP
12Z1-862-1	3	10YR5/1 Gray	2	0.2	HAP
12Z1-862-2	3	10YR7/2 Light gray	2	0.38	
12Z1-866	3	10YR4/1 Dark gray	2	0.16	HAP Quartz
14Z1-0765	5	10YR8/1 White	3	0.84	HAP
14Z1-0161	4	10YR5/1 Gray	4	0.43	HAP
12Z1-2095	5	N 8/White	3	0.45	HAP Calcite Quartz
12Z1-2103-1	1	Z23 10YR4/1 Dark gray	2	0.28	HAP Calcite Quartz
12Z1-2103-2	1	Z24 10YR8/2 Very pale brown	2	0.27	HAP Quartz
14Z1-1571	1	10YR6/2 Light brownish gray	2	0.32	HAP Quartz
12Z1-1729	4	10YR4/1 Dark gray	3	0.28	HAP Calcite Quartz
14Z1-1083	3	10YR5/1 Gray	3	0.33	HAP
12Z1-0413	3	10YR5/2 Grayish brown	3	0.39	HAP Calcite

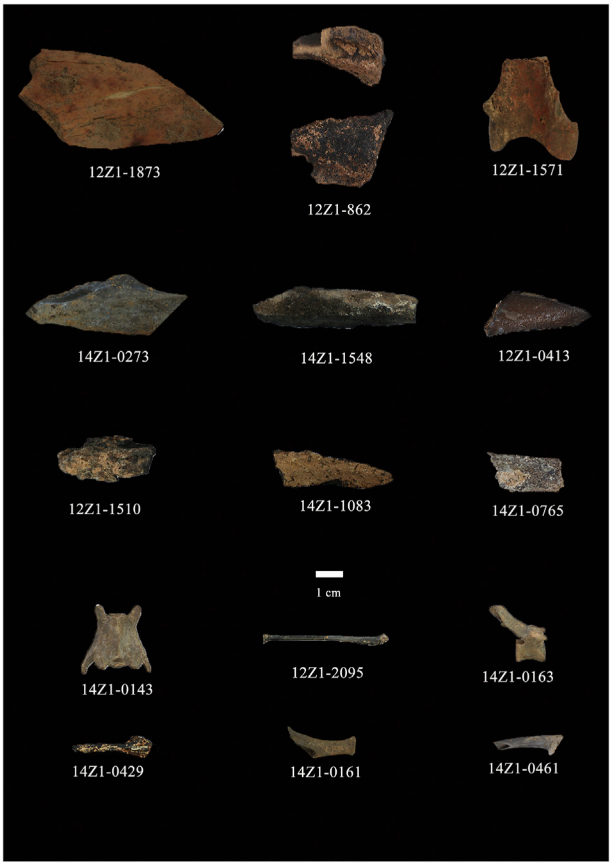

FIGURE 4 | Appearance of bone samples with CI values >0.3, indicating the samples were heated to 600°C or above.

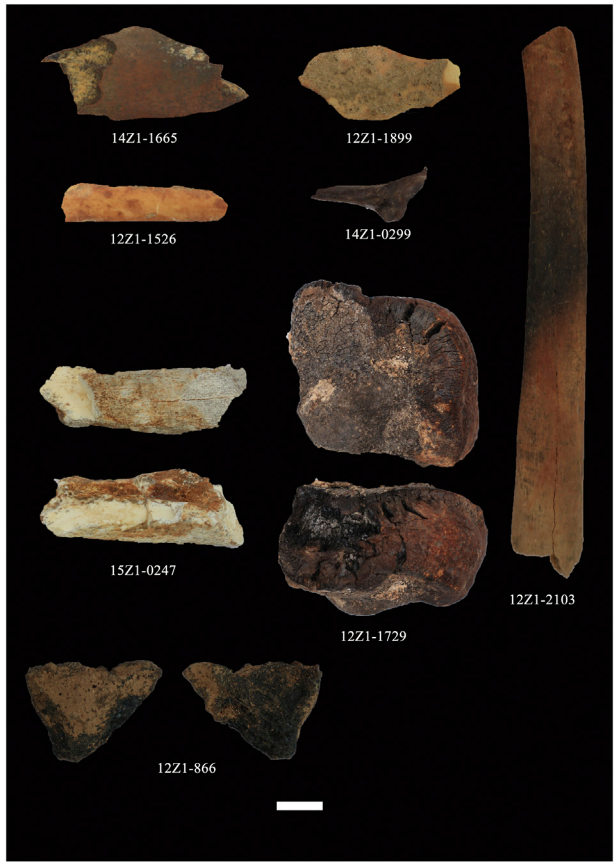

FIGURE 5 | Appearance of bone samples with CI values <0.3, indicating the samples were probably heated to temperatures lower than 600°C.

confirmed that there was no sign of burning; we finally settled on a color level of 0 rather than 6.

We also observed a typical "sandwich" coloration in sample 12Z1-862 (see **Figures 2**, **4**; Buikstra & Swegle, 1989; Barkai et al., 2017). The coloration in intracortical tissue was different with respect to that observed on the outer side, as occurs when bone elements are subjected to partial heat or incomplete combustion while maintaining their fat content (Cerdá et al., 2005). We collected inner and outer powder samples for XRD analysis. In sample 12Z1-2103 (see **Figure 5**), two areas of cortical bone were observed to differ greatly in color, the middle area appearing black while the other areas were reddish brown. We also collected powder samples from these two different color regions for XRD analysis.

XRD Analysis

The XRD pattern of all samples are shown in **Figures 6**, **7** (all raw data are listed in the supplementary materials).

The XRD mineral study indicated similarity among the samples, with hydroxyapatite present in all samples and calcite ($CaCO_3$) in some, as well as quartz (SiO_2; see **Table 3**). These mineralogical compositions are far different from that presented by unaltered, fresh bone (**Figure 8**). With respect to crystallinity measurements, the CI ranged from 0.15 to 0.84 (**Table 3**).

DISCUSSION

The results we obtained through macroscopic observations and XRD analysis show undoubtable proof that the fossil bones from Layer 4 were burned.

Darker colorations in fossil bones usually indicate they have been subjected to thermal events. The coloration of bone is thus a commonly used characteristic to identify past events of burning. Several experimental studies have identified heating temperature from bone color (Shipman et al., 1984; Nicholson, 1993; Stiner et al., 1995). But in our study, we can see that the range of color does not accurately represent degrees of heating between fossil bones. In our previous research, we found that the CI values for all pretreated bones heated above 600°C were above 0.3 (**Table 4**; Huang and Zhang, 2021). And bones burned at high intensity can be clearly recognized from other archaeological bones by XRD patterns and CI values (Lebon et al., 2010). This means a total of 15 bone samples, which CI values above 0.3, were likely burned at 600°C or even higher (**Table 3**; **Figure 4**).

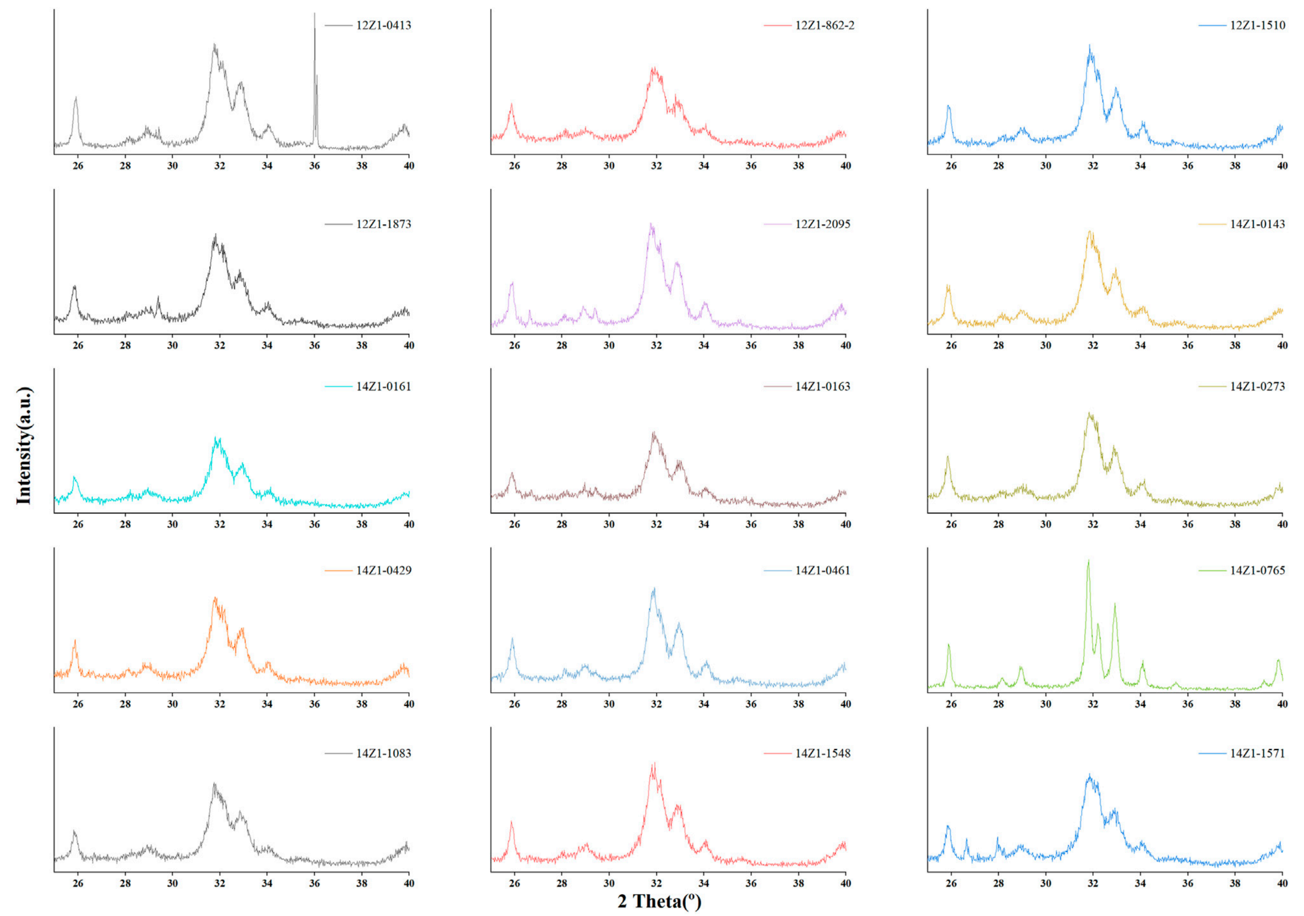

FIGURE 6 | XRD pattern of fossil bone with a higher crystallinity (> 0.3) of hydroxyapatite.

The color of bone can be used to distinguish the intensity of burning in experimental conditions (Shipman et al., 1984). In archaeological bone, color is not a reliable criterion. There are multiple distractions that can affect judgment, such as oxide staining (Shahack-Gross et al., 1997) or taphonomic effects (Behrensmeyer, 1978). Sample 15Z1-0247 from Layer 5 is a fossil bone without any macroscopic characteristic of burning, even though it matched a Munsell color code similar to 14Z1-0273 and 14Z1-0461, which have obvious burned textures (**Figure 4**). The whitish coloration of sample 15Z1-0247 seems rather to indicate a diagenetic effect because it also has a low CI value and presents precipitation of manganese oxides. As a check for burning intensity, examining the texture of bone is indispensable (Cain, 2005).

In sample 12Z1-866, the observed coloration and texture shows a similar result for a high burning degree. However, the CI value for the sample is 0.16, meaning a very low burning intensity (the CI value of 15Z1-0247 is 0.15); moreover, the peaks of hydroxyapatite are not clear from the XRD pattern (**Figure 7**). We confirmed that sample 12Z1-866 experienced only very low levels of combustion through XRD analysis, showing its importance as a method of determining combustion events even if color and texture appear to suggest burning.

The "sandwich" coloration was detected in sample 12Z1-862 as we took two powder samples from different color areas on 12Z1-862 (see **Figure 2**). The Munsell color of the powder shows that 12Z1-862-1 (taken from the outer side) is gray while 12Z1-862-2 (taken from the middle) is light gray. This means 12Z1-862-2 shows a higher intensity of burning, as supported by the corresponding CI values (see **Table 3**). Similarly, we examined the CI values of two parts of different color from sample 12Z1-2103 (**Figure 2**). Despite the obvious color differences between the two regions, their CI values are very close, both lower than in charry or calcine bone. This means the whole bone was subjected to a low degree of combustion. Considering that it is part of a rib, this bone with patches of black alteration, burned at low intensity, may be robust evidence of hominin maintenance and use of fire at Layer 4 (Zhang et al., 2020).

The mineral phase of bones undergoes significant changes while burning. The original mineral in bone is a carbonate-hydroxyapatite, not hydroxyapatite (Elliott, 2002; Monge et al., 2014; Schmahl et al., 2017). With increased temperature, the carbonate will leave the bone and, from about 500 to 600°C, the bone mineral progressively reacts to form hydroxyapatite with increasing purity and crystallite size as temperature continues

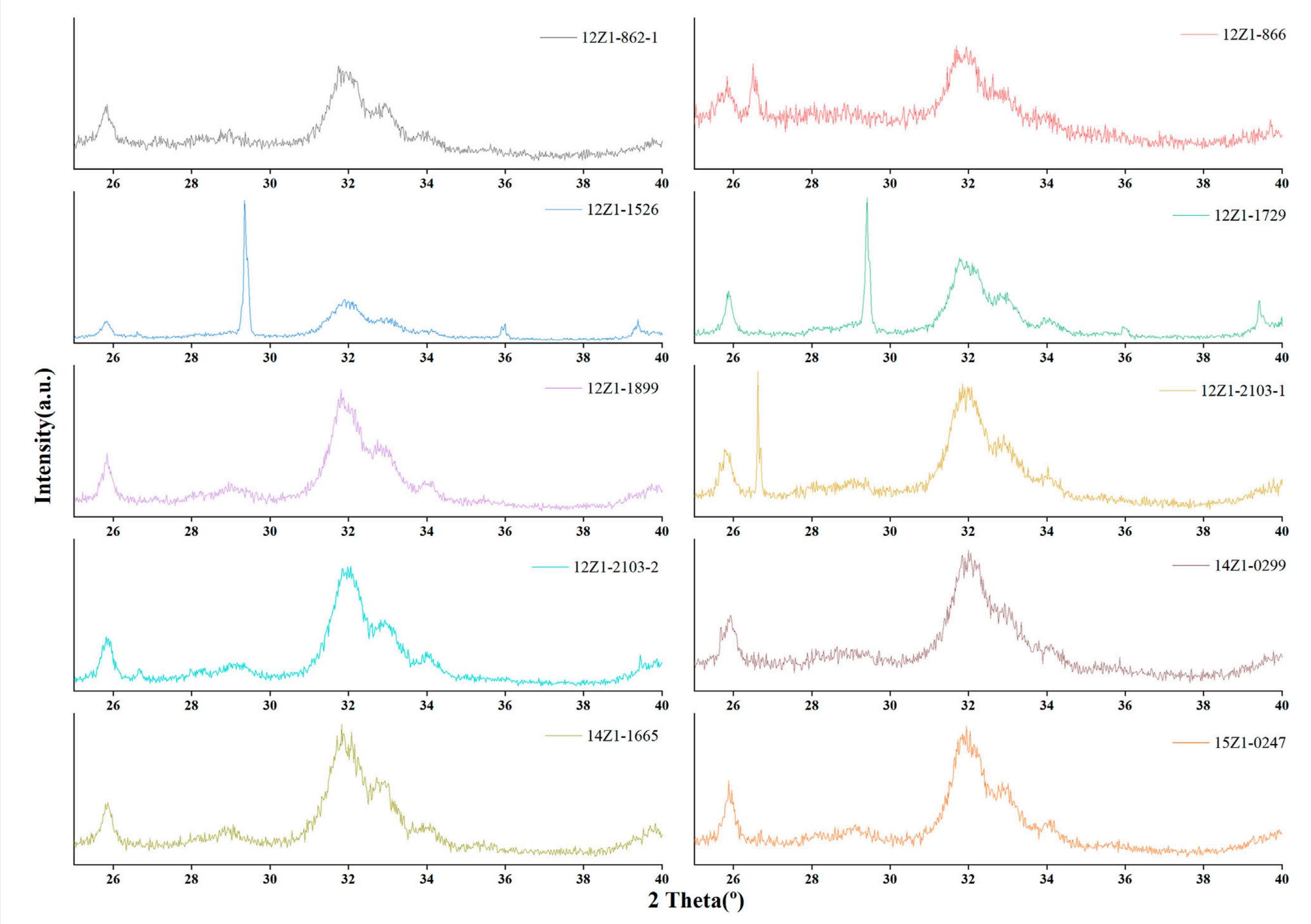

FIGURE 7 | XRD pattern of fossil bone with a lower crystallinity (< 0.3) of hydroxyapatite.

to increase (Shipman et al., 1984; Rogers and Daniels, 2002; Schmahl et al., 2017; Mckinnon et al., 2020).

The XRD pattern for 12Z1-1526, as well as its low CI values of hydroxyapatite (**Figure 7**) and corresponding to its grade of color and texture, shows that its main mineral phase is calcite rather than hydroxyapatite. We can also see that in a bone burned at high intensity, such as 14Z1-0765, the peaks of calcite are absent from the XRD pattern while the CI value of hydroxyapatite is high and its peaks are sharper (**Figure 6**).

Meanwhile, quartz is found in some fossil bones through XRD analysis. This quartz could be related to diagenetic processes and secondary calcite (Monge et al., 2014).

The presence of whitlockite [$Ca_9(Mg,Fe^{2+})(PO_4)_6(PO_3OH)$] also shows thermal events (Monge et al., 2014), but whitlockite is absent from our samples. This may be due to the small number of burned bone we sampled, especially as they show evidence of burning at high intensity. In our previously study, we confirmed that calcium phosphate tribasic [$Ca_3(PO_4)_2$] presented in some experimental calcine bones (Huang and Zhang, 2021). Greiner et al. (2019) also reported the presence of $CaNaPO_4$ in bones with high degrees of burning. Those phosphatic phases may show decomposition of hydroxyapatite at elevated temperatures.

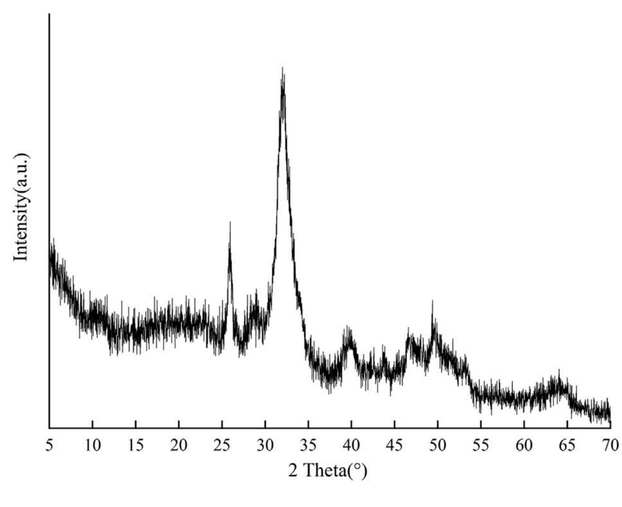

FIGURE 8 | XRD pattern of fresh bone.

In earlier studies at Zhoukoudian Locality 1, the results of elemental carbon analysis suggested that the burned items were probably burned *in situ* (Shen, 2004). Spatial analysis of

TABLE 4 | Crystallinity index values of three pretreated bones (duration: 120 min).

Temperature (°C)	Fleshed bone	Defleshed bone	Degreased bone
550	0.188	0.120	0.295
600	0.375	0.373	0.408
650	0.884	0.656	0.506
700	0.959	0.928	0.825
750	0.936	0.914	0.778
800	0.951	0.957	0.913

Zhoukoudian Locality 1 showed that stone tools and the burning of fresh bone associated with *Homo erectus pekinensis* supported a model of transient hominid scavenging aided by fire (Boaz et al., 2004). Analyses of sediments from the locality also provided evidence of *in situ* use of fire by *Homo erectus pekinensis* (Zhong et al., 2013; Zhang et al., 2014). These findings supplied new technical evidence of the use of fire by *Homo erectus pekinensis*. Along with re-excavation, new data on phenomena of *in situ* fire use have been discovered from Layer 4 (Gao et al., 2017). Based on these findings, our study recognizes bones from Layer 4 that were heated to above 600°C, likely resulting from hominids' use of fire. Gowlett et al. (2017) argued that temperature is not a reliable parameter in recognizing grass fires and human-controlled fires: both range through 200–800°C. However, grass fires would not last long. During the formation of Layer 4, parts of the cave roof remained at Zhoukoudian Locality 1 (Gao et al., 2017), meaning the environment probably did not support many weeds, let alone shrubs. Therefore, the available evidence does not support the existence of large, prolonged wildfires in Layer 4. The high intensity of burning in fossil bones is most likely the result of hominins using fire.

CONCLUSION

Macroscopic observation is regularly used to identify burned bone from archaeological sites, but it is not reliable in some cases because of taphonomic or diagenetic effects. Therefore, technological method such as XRD analysis (an efficient method for identifying burned bones) is necessary. It can be used to calibrate our recognition of burned bones and find degrees of burning in bones. Future studies can focus more on phosphate formation and transformation of hydroxyapatite during burning and the process of diagenesis.

It has been demonstrated that the bones excavated from Zhoukoudian Locality 1 Layer 4 were heated to different degrees in this study. Evidence of thermal events is reflected in their colorations, textures, mineral phases, and CI values. Even though phosphatic phases are absent, the presence of hydroxyapatite and high CI values are enough to suggest that the bones had been burned, most of them to 600°C. These high intensities of burning are most likely the result of hominins' use of fire. Further research should be centered on burned items from the lower layers in order to obtain more evidence of hominin maintenance and use of fire.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

XG designed the study. CH and JL conducted the study. CH wrote the initial version of the manuscript. XG and CH reviewed and edited the final version of manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.811319/full#supplementary-material

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Sustainable Hunting Strategy of Sika Deer (*Cervus nippon*) in the Neolithic Lower Yangtze River Region, China

*Ying Zhang[1,2,3,4], Guoping Sun[5], Yonglei Wang[5], Yunping Huang[4], Hiroki Kikuchi[6] and Xiaoyan Yang[1,2,7]**

[1]Group of Alpine Paleoecology and Human Adaptation (ALPHA), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China, [2]State Key Laboratory of Tibetan Plateau Earth System, Resources and Environment (TPESRE), Beijing, China, [3]Institute of Archaeology, University College London, London, United Kingdom, [4]School of Archaeology and Museology, Peking University, Beijing, China, [5]Zhejiang Provincial Institute of Archaeology and Cultural Heritage, Hangzhou, China, [6]School of History and Culture, Lanzhou University, Lanzhou, China, [7]Key Laboratory of Western China's Environmental Systems (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou, China

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Yue Zhang,
Institute of Vertebrate Paleontology and Paleoanthropology (CAS), China

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Yue Li,
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University of Colorado Boulder, United States
Chong Yu,
Sun Yat-sen University, China

****Correspondence:***
Xiaoyan Yang
xyang@lzu.edu.cn
xyang@itpcas.ac.cn

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Zooarchaeology studies the human-animal interactions over long periods, and can be used to evaluate the sustainable exploitation of animal resources. Sika deer (*Cervus nippon*), a National Class I protected wild animal species of China, used to be commonly found at Neolithic sites across China. In the Yangtze River region, although the Neolithic faunal assemblages show diversity in deer species, sika deer has always been one of the most important components. This research aims at discussing the exploitation of the environmental resources via the hunting strategy of sika deer at Tianluoshan, a Neolithic site in the lower Yangtze River region. The cull pattern and sex ratio of sika deer are reconstructed to display the pattern of prey selection. The results show a specific pattern targeting larger individuals including adults and juveniles, and targeting male over female. This pattern is able to maximize the yield, and keep the deer population sustainable. The sustainable hunting of sika deer probably is why the Tianluoshan site lasted for nearly a thousand years, during which sika deer had been a major prey for meat.

Keywords: zooarchaeology, subsistence economy, culling profile, sex ratio, seasonality, sustainability

INTRODUCTION

Zooarchaeology investigates the human-animal interactions over centuries and millennia, and thus provides irreplaceable tools for evaluating long-term sustainable use of natural resources (Butler and Delacorte, 2004; Frazier, 2007; Lyman, 1996; Wolverton and Lyman, 2012). In the long history of hunting, the unsustainable exploitation, together with other natural and anthropogenic factors, has caused the decline and extinction of many animal species, and this situation is getting more and more serious (Davis, 1987; Boivin et al., 2016; Frazier, 2007). Meanwhile in many cases, although capable of modifying the ecosystem, the exploitation was managed to a sustainable level, represented by the settlements which were inhabited for hundreds or thousands of years. There is a saying in Chinese: history is a mirror for us to see the faults. Zooarchaeology is not only to study the past, but also for the mankind to have a better future. However not realized, the fact is zooarchaeology has helped to reintroduce the extirpated populations of Père David's deer (*Elaphurus davidianus*) in China, and relocate the conservation parks to the Huai River and Yangtze River region which were their original habitat (Cao, 2005).

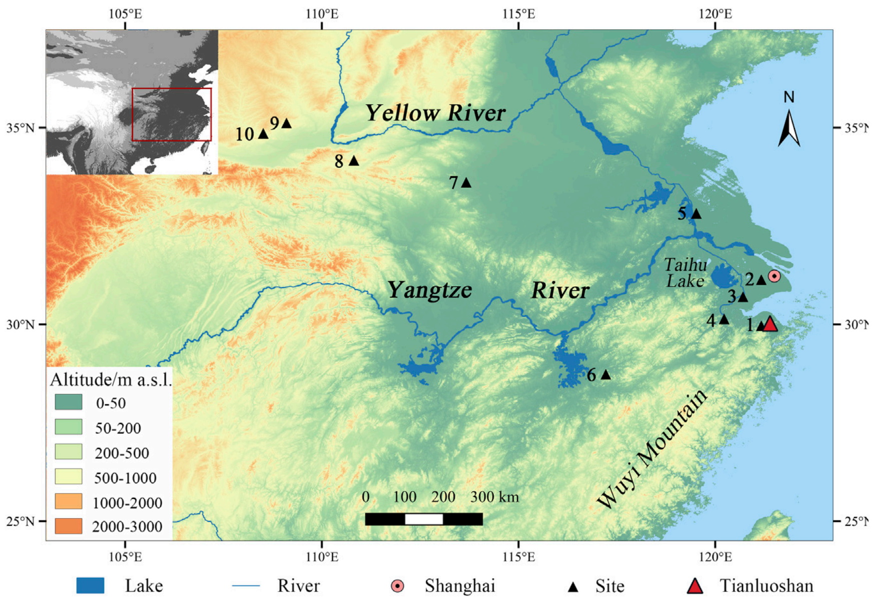

FIGURE 1 | Site location of Tianluoshan and sites with sika deer remains.

Sika deer (*Cervus nippon*) is a medium sized cervid native to East Asia, inhabiting temperate and subtropical forests and shrubs with dense understory (Sheng, 1992; McCullough et al., 2009b). The IUCN Red List of Threatened Species now label sika deer as "least concern", indicating that they are not under the threat of extinction (Harris, 2015). However, a glance at the distribution map shall realize that most sika deer are concentrated in Japan; their distribution area in China is limited into a few isolated patches, which is harmful for population continuity (Guo and Zheng, 1992; Sheng, 1992; Guo and Zheng, 2000; McCullough et al., 2009a). As a matter of fact, the subspecies *C. n. mandarinus*, and *C. n. Grassianus* are already extinct (Guo and Zheng, 1992; Guo and Zheng, 2000). The wild populations of sika deer have been listed as National Class I Protected Wild Animal Species of China (National Forestry and Grassland Administration, 2021).

Archaeological records draw an entirely different distribution map of sika deer in the Neolithic period (approx. 10000–2000 BC). Sika deer remains have been found in sites across China (**Figure 1**) (Institute of Archaeology Chinese Academy of Social Sciences, 1991; Institute of Archaeology Chinese Academy of Social Sciences, 1994; Institute of Archaeology Chinese Academy of Social Sciences, 1995; Henan Provincial Institute of Relics and Archaeology, 1999; Zhang et al., 1999; Zhejiang Provincial Institute of Cultural Relics and Archaeology, 2004; Zhang and Hung, 2008; Innes et al., 2009; Ren and Wu, 2010; Institute of Archaeology Chinese Academy of Social Sciences, Institute of Earth Environment Chinese Academy of Sciences, 2011; Wu et al., 2012), and usually take up a rather high proportion in the faunal assemblage (e.g., Henan Provincial Institute of Relics and Archaeology, 1999; Zhejiang Provincial Institute of Cultural Relics and Archaeology, 2003; Yuan and Yang, 2004; Wang, 2011; Song, 2017; Song, 2019; Li et al., 2021). The hunting strategies of sika deer have been discussed in the past few years, featuring the middle Yellow River region which was an important prehistoric cultural center in China. The study of the Wayaogou site (3400–2700 BC) suggested that deer hunting was organized according to seasonality and the conditions of the deer population (Wang, 2011; Wang et al., 2014). A recent research on the Zaoshugounao (1250–1050 BC) sika deer remains reveals a sustainable hunting strategy that took place in the Bronze Age (Li et al., 2021).

This research intends to investigate whether sika deer were hunted sustainably in the Neolithic Yangtze River region, by interpreting the deer hunting strategy at the Tianluoshan site 7,000 to 6,000 years ago. The culling profile, sex ratio, and death seasons are used to discuss the choice of prey and the hunting seasons, which are key issues in the hunting programme.

1. Hemudu (5000–4000 BC); 2. Songze (3500–3000 BC); 3. Majiabang (5000–4000 BC) 4. Kuahuqiao (6200–4200 BC); 5. Longqiuzhuang (3000–2300 BC); 6. Xianrendong (22550–10000 BC); 7. Jiahu (6100–4800 BC); 8.Xipo (2800–2300 BC); 9. Wayaogou (3400–2700 BC); 10. Zaoshugounao (1250–1050 BC).

SITE DESCRIPTION

The site of Tianluoshan is located in a small valley in Yuyao County, Zhejiang province, in the lower Yangtze River plain (**Figure 1**). It has been under the spotlight since its first excavation in 2004, due to the extremely rich material culture which resembles the famous Hemudu Culture which is known worldwide for rice cultivation 7,000 to 6,000 years ago (Bellwood, 2005; Chang, 1987; Fuller et al., 2009; Scarre, 2018). Radiocarbon dating shows that the site was occupied approximately 5000–4000 BC. As excavations and research went on, it was revealed that

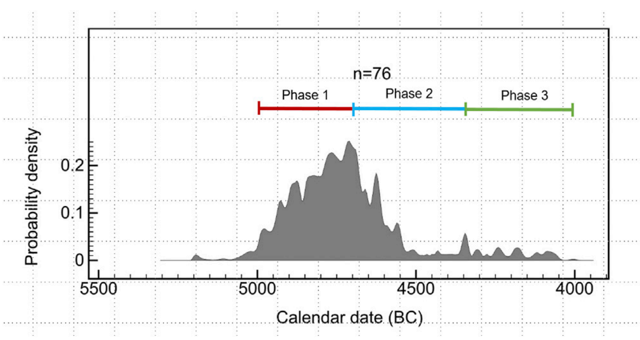

FIGURE 2 | The calibrated radiocarbon dates of Tianluoshan. The dates from 76 samples form a time sequence of Tianluoshan.

Tianluoshan was another representative site of the Hemudu culture, with the typical black pottery, worked bone manufacture, and most importantly rice domestication (Fuller et al., 2011; Fuller et al., 2009; Sun, 2011; Zhejiang Provincial Institute of Cultural Relics and Archaeology, 2003). The researchers divided the culture layers into three phases based on stratigraphy, and this division was also supported by radiocarbon data: phase 1 included layer 8 and 7 and lasted approximately from 5000 to 4700 BC; phase 2 included layer 6 and 5, at 4700–4300 BC; phase 3 consisted of layer 4 and 3, at about 4300–4000 BC (**Figure 2**) (Sun, 2011; Wu et al., 2011; Nakamura et al., 2016). Therefore, the Tianluoshan Neolithic village was inhabited from 5,000 to 4000 BC. The radiocarbon dates are summarized in **Supplementary Table S1**.

The well-preserved materials by the waterlogged environment provided great information to reconstruct the village life six to seven thousand years ago. Plant and animal remains indicated a subsistence economy greatly relied on hunting, gathering, and fishing wild resources such as acorns (*Quercus*), water chestnuts (*Trapa*), fox-nuts (*Euryale*), sika deer (*Cervus nippon*), muntjac (*Muntiacus reevesi*), snakehead (*Channa argus*), crucian carp (*Carassius auratus*), etc. Among the mammalian remains, several species of deer were major prey; sika deer outnumbered the other species e.g. muntjac, sambar (*Cervus unicolor*), and Père David's deer (*Elaphurus davidianus*), indicating sika deer hunting should be an important part in the entire subsistence strategy.

MATERIALS AND METHODS

Research Materials and Sampling

All sika deer remains were collected during the excavations from 2004 to 2010. Medium to large mammal remains, sika deer included, were mainly retrieved by hand collecting. Wet sieving was crucial for retrieving small animal remains, such as fish, small deer, etc., but only contributed a small number of deer, mostly carpals, tarsals, and phalanx. Animal remains were stored by context (trench and layer).

The mammal remains from each context were first separated into "identifiable" and "unidentifiable" categories. The "unidentified" was sorted into large, medium, and small mammals based on the bone size and shaft thickness. The "identifiable" was further sorted by element, and then identified to family, genus, and species if possible, using the reference collection in School of Archaeology and Museology, Peking University; published atlases were also used in identification (Schmid, 1972; Hillson, 1992, 2005; Matsui, 2001-2005). The results of species/genus, element, ageing, sexing, worked traces, gnawing traces, and measurements were recorded in a database. Number of Identified Specimens (NISP) and Minimum Number of Individuals (MNI) were used for quantitative analysis (Grayson, 1984; Lyman, 2008; Reitz and Wing, 2008).

Sika deer remains from the faunal assemblage were taken for further observation, and the sika deer records were selected from the database for quantification. The mammalian assemblage contained 13718 pieces of remains, and 6,378 pieces could be identified to order, family and beyond. The total number of sika deer remains was 2486, was the largest in the identifiable specimens (**Figure 3**). 341 sika deer specimens were identified from phase 1, taking up 36.7% of the identifiable mammalian specimens; 1618 were from phase 2, taking up 38.3% of the mammalian NISP, and 527 were from phase 3, taking up 43.4% of the NISP. For the concerning of sample size, 141 mandibles from both sides were used for dental ageing, including 30 mandibles from phase 1, 87 from phase 2, and 24 from phase 3. The mandibles were checked not to be paired morphologically.

Ageing and Sexing Sika Deer

Dental records and the epiphyseal fusion of postcranial bones have been widely used to estimate the age at death of a mammal in zooarchaeology (Grant, 1982; Silver, 1969). The ageing and sexing methods for different deer species have been developed based on the research of modern specimens. Tooth eruption, development, and replacement show precise age of fawns, juveniles, and sub-

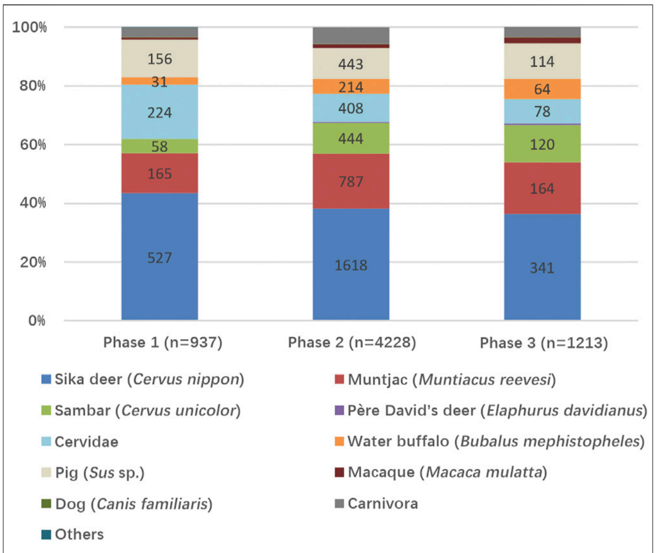

FIGURE 3 | Mammal species and relative proportions of Tianluoshan.

adults (Brown and Chapman, 1991a; Koike and Ohtaishi, 1985; Sheng, 1992). For adults, attritional wear on the occlusive surface is commonly used, by reading the wear pattern or using a scoring scheme (Brown and Chapman, 1991b; Brown and Chapman, 1990; Chapman et al., 2005; Ohtaishi, 1980). Crown height measurement and count of annuli in cementum are also used (Klein et al., 1981; Koike and Ohtaishi, 1985). The epiphyseal fusion on postcranial bones of fallow deer (*Dama dama*) has been researched (Carden et al., 2006).

As sika deer has been the one and only native deer species in Japan, Japanese scholars contributed plenty work in relative research (Ohtaishi, 1975, 1976, 1978, 1980; Koike and Ohtaishi, 1985, 1987; Ohtaishi and Gao, 1990; Sheng et al., 1998; Uchiyama, 1999; McCullough et al., 2009b). Ohtaishi and colleagues established the sequence of teeth eruption, replacement, and wear by studying modern sika deer in Japan, and applied to reconstruct the death age and cull pattern of the sika deer remains from Jomon sites (Ohtaishi, 1980; Koike and Ohtaishi, 1985, Koike and Ohtaishi, 1987). There was also an attempt to apply Brown and Chapman's scoring scheme on red deer to sika deer (Wang et al., 2014). As Ohtaishi's approach is easy to use, here we employ Ohtaishi's methods to estimate the death age of each sika deer individual, to generate the cull pattern of the captured sika population, and to discuss the hunting strategy at Tianluoshan.

Female and male sika deer are different morphologically, and sexing skeletal parts are usually undertaken by two means. First, the presence and absence of antlers on cranium. Male deer (stags) start to grow antlers in the second summer after birth, and bear full antlers at 3–4 years old; females do not grow antlers throughout their lives (Hayden et al., 1994; Yang et al., 1990). Second, sexual dimorphism exists between two sexes: body measurements of adult males averages 8.7% greater than those of females (Feldhamer, 1980). The measurements of the postcranial bones may show the difference, but the existence of juvenile and sub-adult individuals can blur the boundary. Research showed that the measurements of mandibles and dental sequence show the indication between females and males (Uchiyama, 1999). In this research, we attempt to use cranium and mandibles to analyze whether there was a preference of sika deer sex in hunting.

A-C represent 3 life-stages of sika deer: A-fawn, B-juvenile, and C-adult. The span of each block represents the time length of the life-stage: fawn–1 year, juvenile— years, and adult—10 years. The "abundant" life-stages are shown by the larger letters. The histograms are recreated using data from Koike and Ohtaishi (1987).

Cull Pattern and Sex Ratio Reflecting Hunting Strategy

The lifespan of captive sika deer is 15–18 years, but wild individuals rarely live over 10 years (Ohtaishi, 1978; Koike and Ohtaishi, 1985; Landesman, 1999). The life history of sika deer can be classified into three life-stages: fawn (under 1 year old), juvenile (1–4 years old), and adult (5 years and older). Sika deer of different life-stages show different biological features and act differently, so the following age profiles shall be named after these terms.

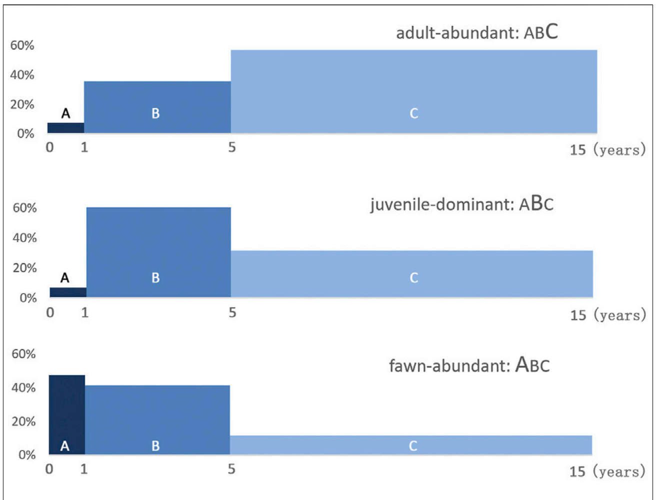

FIGURE 4 | Age compositions of the three sika deer hunting patterns.

Koike and Ohtaishi (Koike and Ohtaishi, 1987) established three models for age structure based on their research on the archaeological remains from 14 sites: adult-abundant pattern, which contained over 60% adults, represented by Ishiyama shell midden site (Early Jomon period, about 5000–3520 BC); Juvenile-dominant pattern, in which the proportion of juveniles is around 60%, represented by Fuyuki site of Late Jomon period (2470–500 BC); and fawn-abundant pattern represented by Onnemoto site of Okhotsk culture. These three patterns are modified using original data, and displayed by life-stages (**Figure 4**).

Cull pattern can reflect the hunting techniques. A cull with age composition similar to the live population is to be expected from random-capture harvesting by intensive trapping techniques such as the drive-in traps; and the proportion of young animals may be slightly higher as some older ones are likely to escape the traps based on their experience. By contrast, hunting techniques that targeting single animals, such as with a bow and arrow or gun, should produce stronger selection among the game animal. The indicator for distinguishing two hunting techniques is the frequency of fawns and yearlings: a high frequency of fawns and yearlings refers to catastrophic hunting such as trapping, while a low frequency indicates individual hunting. Therefore, the three models indicate different hunting techniques that were used at the sites. Individual hunting was practiced at Jomon sites such as Ishiyama and Fuyuki, and trapping was used at Onnemoto, an Okhotsk Culture site.

Seasonality Reconstruction

The hunting seasons are important for us to learn about the exploitation of the animal resources, and labour and time management of year. Sika deer have regular life cycles that breeding and birth occur in fixed time of year. According to the research on the modern sika deer population in the lower Yangtze River region, breeding occurs from September to December, and birth occurs around mid-May (Yu, 2008).

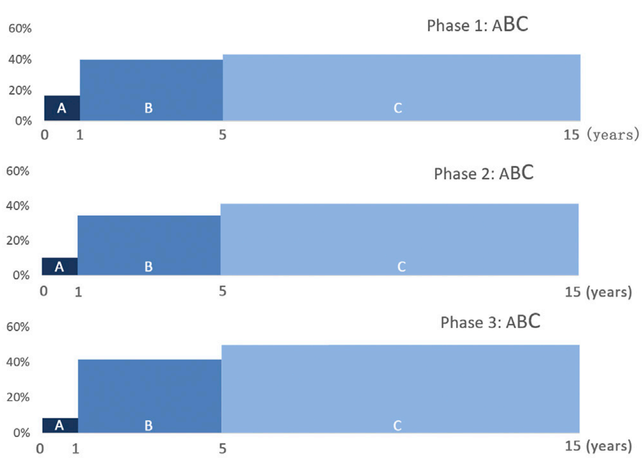

FIGURE 5 | Cull patterns of Tianluoshan sika deer. **(A)**: fawn; **(B)**: juvenile; **(C)**: adult. The span of each block represents the time length of a life-stage: fawn–1 year, juvenile—4 years, and adult—10 years. Large letter indicates a high proportion of the life-stage.

Antler shedding is also seasonal, which occurs in april and May, and thereafter stags grow a new pair during summer to get ready for the rutting season in autumn (Yang et al., 1990).

The hunting season of sika deer is estimated by means of two approaches. First, the death season of an individual can be calculated by adding the age at death which is already estimated for cull pattern reconstruction, to birth month. In order to get a precise result, we only choose the individuals younger than 2 years old, the age of which are estimated from teeth eruption and replacement. Second, the presence, absence, and the structure of antlers represent the death season of the stag. The stag bears antler from June to March the next year, and hunting during these months shall get deer with antlers growing stiffly on the heads (Yang et al., 1990). During the early time of the antler-growing cycle, also known as the velvet antler period, the structure of the antler is spongy, thus it shall indicate a very specific time of hunting. If hunting occurs when the stags shed antlers, the skull shall only have antler base with a flat natural shedding surface on top.

RESULTS

The Adult-Abundant Cull Pattern

The cull pattern distributions of three phases share similarities. First, the age span in each phase is wide, containing individuals from under 1 year old to over 8 years old. The teeth of sika deer older than 8 years old are heavily worn, thus the death age cannot be estimated accurately. The percentages of adults is 43.3% in phase 1, 41.4% in phase 2, and 50% in phase 3, and juveniles is 40% in phase 1, 34.5% in phase 2, and 41.7% in phase 3, respectively. The proportions of fawns are quite low, 16.7% in phase 1, 10.3% in phase 2, 8.3% and in phase 3, respectively, decreasing slightly through time (**Figure 5**).

The Tianluoshan cull patterns can be classified as the adult-abundant pattern, as the adult individuals have the highest proportions (40–50%), although do not reach the proportion of the model pattern (60%). The proportions of the juveniles and fawns are also higher than the adult-abundant pattern. Therefore, the Tianluoshan pattern can be seen as the adult-abundant pattern with a few juvenile and fawn factors.

Sex Ratio Shows a Preference of Male Deer

28 fragments with frontlets are recorded in this study, and 27 of them have antler bases attached, indicating male predominance. As cranial fragments are difficult to identify to species, the proportion of male sika can be exaggerated.

Therefore, we also examine the measurements on the mandibles following Uchiyama's (1999) procedure. The height of anterior mandible (a) and the length of premolar sequence (PL) were measured, both of which were related to age and sex due to bone development. As both measurements were taken on the mandible rather than on teeth, they were not influenced by tooth attrition. The mandibles which show information of age are marked separately.

Three clusters of plots can be recognized in **Figure 6**. Group A is the smallest in measurement, and mainly consist of fawns and yearlings. The developing mandibles bring variety to this group. The mandible size of group B is larger than group A, and possibly consist of females; sub-adult males may also fall in this group. Group C is the largest in measurement, possibly representing the males. Group C also has the largest number of individuals (n = 31), comparing to group A (n = 11) and group B (n = 16), indicating that adult male were hunted more frequently than the females. All measurements for this analysis can be found in **Supplementary Table S2**.

In brief, both female and male sika deer were captured, and male deer were hunted more frequently.

Seasonality

24 mandibles representing 24 individuals under the age of 2 years old were carefully examined, their age were identified to month. Research shows that the rutting season of sika deer in the Yangtze River region is from August to November, and the birth of fawns

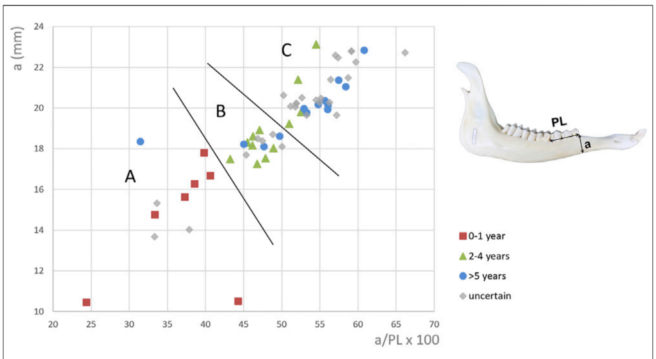

FIGURE 6 | Mandible measurements showing sexual dimorphism. The plots cluster into three groups: **(A)** fawns and yearlings; **(B)** females and young males; **(C)** males.

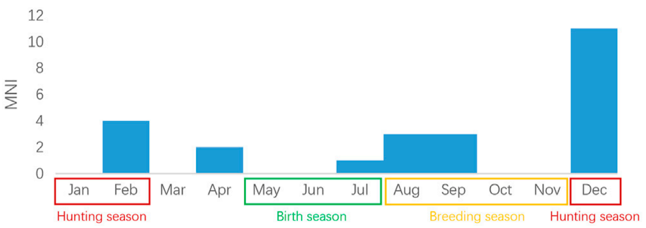

FIGURE 7 | Distribution of the death month of sika deer from Tianluoshan.

occurs from May to July, mostly in June. give birth to the fawns in mid-May (Yang et al., 1990). Here we use June as the birth month for the calculation of death month.

Over half (15 individuals) were killed in winter from December to February the next year (**Figure 7**). Sika deer hunting also occurred in the other three seasons, but less frequently. The antler growth and shed cycle agreed with the dental ageing. Sika stags start to grow a new pair of antlers in April-May, and wear them throughout the year until april the next year (Yang et al., 1990). 26 out of the total 27 male frontlets have antlers attached, indicating that hunting mostly took place between summer and the next spring.

Therefore, winter hunting could avoid the birth season, and diminish the harmful effect to the population, indicating that deer hunting was conducted based on the knowledge of sika deer's life history.

DISCUSSION

The Sika Deer Hunting Strategy at Tianluoshan

From the cull pattern, sex ratio, and seasonality analysis above, we can now draw an image of the sika deer hunting strategy practiced at Tianluoshan 7,000–6,000 years ago.

First, adults and juveniles were preferred, possibly to maximize the hunting profit. According to the body growth model of sika deer, body weight increases rapidly until 3 years, stabilizes until about 10 years, and gradually declines thereafter (Miura and Tokida, 2009). The adults and many juveniles fall into this range, indicating that the hunting prey were chosen, probably by their body size.

Second, the sika deer cull patterns indicate that single animals, rather than the deer population, were targeted in each hunting. Hunting strategy which targets the entire population, such as the drive-in traps, can result in a cull pattern that similar to the live population, with large proportions of fawns and yearlings. By contrast, hunting techniques that targeting single animals, such as guns, bows and arrows, should produce stronger selection among the game animals, e.g., the larger individuals or animals bearing larger antlers, to get a better return. Therefore, the fawn-abundant pattern can be interpreted as population hunting. The adult- and juvenile-abundant patterns, on the other hand, can be seen as the results of individual hunting. We may propose that the Tianluoshan people were targeting one or a few sika deer in each hunt.

Third, both male and female sika deer were hunted, but males were probably hunted more frequently than the females. Due to sexual dimorphism, male sika deer are larger than the females. Therefore, hunting males can get a better return, including meat and antlers for making tools.

Fourth, sika deer was an important stable meat resource for the Tianluoshan residents throughout the year, and was even more important for them to overcome the food shortage in winter. Seasonality analysis shows that deer hunting was practiced in different months of year, and more frequently in winter time. Similar hunting calendar was used by the Neolithic Jomon people living on the Japanese archipelago, that sika deer were mostly hunted in winter time (Habu, 2004; Kobayashi, 2004). The body weight of animals usually varies between different seasons. Research on the modern sika deer revealed that sika deer was heaviest in autumn, with a mean body weight of 62.6kg, and would lose a few kilos in winter (mean body weight 57.4 kg) (Masuko and Souma, 2009).

The Sustainable Hunting of Sika Deer

The culling profiles, sex ratio, and hunting seasons indicate that a sustainable hunting strategy was practiced at Tianluoshan. In the sika deer population, adult male deer were mostly targeted; conversely, the proportions of females and fawns were rather low. This selection of prey left out females and fawns which were crucial for population reproduction. Most hunting took place in winter, avoiding the rutting season in autumn and the birth seasons from May to July.

In the study of modern animals, life table and survivorship curves are commonly used to examine the life history of a population. The survivorship curve is displayed by the logarithm of the frequency of surviving individuals against age. There are three theoretical survivorship curves showing

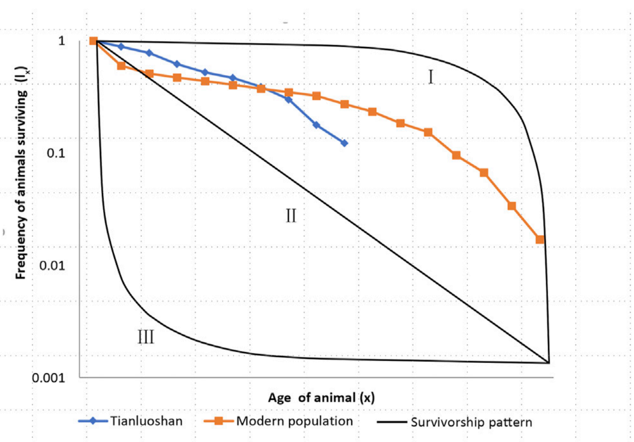

FIGURE 8 | The survivorship curves of Tianluoshan and modern sika deer. The frequency of individuals surviving is plotted on a logarithmic scale on the Y axis against the age of animal on the X axis. The survivorship curves I, II and III are theoretical curves following Deevey (1947).

different life history patterns according to Deevey (1947) (**Figure 8**). The type I curve indicates that the animals have a high survivorship rate until old age, represented by large animals e.g. elephants. The type III indicates a high level of mortality at a very young age, but the survivors have a good chance of reaching maturity. The type II curve lies in between, indicating that the probability of death remains constant throughout life. Most animals' survivorship curves fall into type I and type II or intermediate. Reef fish and oysters fall into the type III range.

The survivorship curve of Tianluoshan sika deer is generated from the cull structure. Due to the similarity between the cull structures of three phases, the individuals are added together as a large sample. The survivorship curve of modern sika deer is generated following Koike and Ohtaishi (1987), a stationary population protected from hunting. The survivorship curve of Tianluoshan sika deer fall into the area between type I and type II. It has lower mortality rate for fawns and individuals younger than 6 years old than the protected population, but the mortality rate for adult individuals older than 6 years old increases significantly (**Figure 8**). Clearly hunting has influenced the survivorship of the sika deer population near Tianluoshan, especially comparing to the Japanese population which only face natural death and predators; but the hunting strategy that deliberately avoid young individuals did not threaten the population. This probably is why the Tianluoshan site lasted for nearly a thousand years, during which sika deer had been a major prey for meat.

CONCLUSION

This research interpreted the sika deer hunting strategy at the site of Tianluoshan, from the perspectives of culling profile, sex ratio, and death seasons. The results show that sika deer were hunted individually, and adult male deer were preferred over females and fawn, possibly for the consideration of maximize the harvest; although sika deer could be hunted throughout the year, the hunting mostly took place in winters, avoiding the breeding seasons in autumn and spring. All the factors indicate that deer hunting was conducted orderly, following the rules of population sustainability. This hunting strategy supplied the Tianluoshan people with stable and consistent food resources, so that the Hemudu culture could develop prosperously.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

YZ, GS, and XY contributed to conception and design of the study, and funding acquisition. GS and YW contributed to the investigation of the research materials. YZ organized the database, performed the statistical analysis, and wrote the first draft of the manuscript. YH and HK contributed sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.812910/full#supplementary-material

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Diachronic Change in the Utilization of Ostrich Eggshell at the Late Paleolithic Shizitan Site, North China

Yanhua Song[1], *David J. Cohen*[2]* *and Jinming Shi*[3]

[1]*Department of Archaeology, Shanxi University, Taiyuan, China,* [2]*Department of Anthropology, National Taiwan University, Taipei, Taiwan,* [3]*Shanxi Museum, Taiyuan, China*

Forty-one ostrich eggshell (OES) artifacts excavated at five localities of the late Paleolithic Shizitan site, on the North China Loess Plateau, allow the observation of diachronic changes in the utilization of ostrich eggs in the production and use of ornaments considered to be technologies of social signaling, beginning during the Last Glacial Maximum (LGM) and continuing through the Younger Dryas. Based on changes in dimensions, production techniques such as drilling, coloration through heat treatment or the application of ochre, and stringing techniques, the OES pendant and bead use at Shizitan is divided into four phases. Phases 1–3 feature only completed ornaments, usually with heavy usewear. Only in Phase 4, during the Younger Dryas, blanks and drilled preforms are found that indicate local production. While Phase 1 features the use of larger pendants colored grey/black by burning, subsequent phases see beads replacing pendants, no heat coloration, and the use of the ochre pigment. The switch to beads corresponds with the change to microblade technology at Shizitan 29. Phase 3 shows a trend toward a larger relative surface display area and maturation of techniques to produce visual effects of roundedness and weightiness. Phase 4 local production shows technological developments that allowed drilling smaller apertures while also decreasing the bead diameter and increased standardization, implying changing display objectives (stringing beads together with a uniform appearance). The changes observed in the Shizitan diachronic dataset may relate to changing requirements in social signaling—part of the adaptations the hunter–gatherer groups made to survive the challenges of climatic change from the LGM through the Terminal Pleistocene in North China.

Keywords: ostrich eggshell, non-edible utilization, perforated ornaments, ornament coloration, drilling techniques, social signaling, Last Glacial Maximum, Shizitan site localities

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Evgeny Rybin,
Institute of Archaeology and Ethnography (RAS), Russia

****Correspondence:***
David J. Cohen
dcohen@ntu.edu.tw
orcid.org/0000-0002-5973-8566

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INTRODUCTION

The use of ostrich eggshell as a raw material for Paleolithic mobile hunter–gatherer artifact production is well-documented in regions then inhabited by ostriches, particularly in Late Stone Age contexts in Africa and Upper (or Late) Paleolithic contexts in northern Asia (Wingfield, 2003; Hitchcock, 2012). The most common, but still rare, usage known is for making personal ornaments—non-utilitarian items in the form of drilled beads or pendants that are interpreted as aesthetic items that hold a symbolic value and may function as technologies of communication and social signaling (Kuhn S. and Stiner, 2007; Kuhn S. L. and Stiner M. C., 2007; Kuhn, 2014; Stiner, 2014) or in reinforcing hunter–gatherer reciprocity networks, particularly in times of stress (Vanhaeren, 2005). Other ostrich eggshell items could have held similar roles, such as abstract representations engraved on ostrich eggshell,a form of portable art (Miller and Willoughby, 2014). Ostrich eggshell (OES) ornaments have been reported from sub-Saharan African Late Stone Age and possibly Middle Stone Age contexts (e.g., Deacon, 1995; Robbins et al., 2000; Vogelsang et al., 2010; d'Errico et al., 2012), and East African sites (perhaps first appearing 50–39 ka BP) (e.g., Mehlman, 1991; Miller and Willoughby, 2014), and sites in North Asia by 37 ka cal BP (or perhaps earlier), including Siberia (Denisova Cave in the Russian Altai), Mongolia (Tobor 4, Tolbor 16, and Dörölj 1), and the Transbaikal region (at Podzvonkaya localities) (Tashak, 2002a; Tashak, 2002b; Jaubert et al., 2004; Derevianko et al., 2006; Kuzmin et al., 2011; Mellars et al., 2013; Rybin, 2014; Zwyns et al., 2014; Wei et al., 2017). Where appropriate data are available, the archaeological distributions beginning from ca. 50 ka BP of such non-edible animal resources as OES can be taken as indicators of mobility patterns or the social geography of modern humans or used in models of diffusion and exchange through social networks (e.g., Mcbrearty and Brooks, 2000; Stiner, 2014; Abadía and Nowell, 2015; Stewart et al., 2020 and references therein).

In China, ostrich (*Struthio* sp.) eggshell ornaments are rare but are found beginning from ca. 34 Ka cal BP at Upper, or "Late", Paleolithic sites in North China, including localities of the Shuidonggou site (Chen et al., 2012; Gao et al., 2013; Pei et al., 2014; Wang et al., 2015) and the Gezishan site (Guo et al., 2017) in Ningxia, the Shizitan site in Shanxi (Shizitan Archaeological Team, 2010; Shizitan Archaeological Team, 2013; School of History and Culture, Shanxi University and Shanxi Provincial Institute of Archaeology, 2017; Song et al., 2017), and at Xishahe (Guan et al., 2020) and other localities in the Nihewan Basin in Hebei (Chen et al., 2012; Gao et al., 2013; Pei et al., 2014).

At Shuidonggou localities SDG 2, 7, and 8, OES ornaments are found in "advanced core and flake" contexts from ca. 34–27 Ka cal BP (Li et al., 2019), along with the usage of stone grinding slabs, bone needles, and ochre pigment. Shuidonggou 2 features six OES beads artificially colored with an ochre pigment compound, found in a layer dating 31 Ka cal BP (Pitarch Martí et al., 2017). At the Xishahe locality in the Nihewan Basin, OES fragments are found in an early occupation layer (3B), with one piece directly radiocarbon dated to ca. 29 Ka cal BP, and one biconically drilled ostrich shell bead fragment was recovered from the earliest microblade-producing level (3A), dating ca. 27 Ka cal BP, which is one of the earliest microblade contexts in North China (Guan et al., 2020). Similarly, at Shizitan, OES ornaments are first produced in "advanced core and flake" industry contexts and continue to be in use when microblade production begins at Shizitan 29 during the Last Glacial Maximum, between 26 and 24 Ka cal BP (Song et al., 2017). Below, we discuss the development of the OES ornament productions at Shizitan, which continues through the Terminal Pleistocene. Because of the overall scarcity of all ornament types in Paleolithic North China, including OES ornaments, or any other preserved material culture related to symbolic behavior, communication, and art and behavioral modernity (see Bar-Yosef, 2007), the OES data set from the controlled excavations of seven contexts across five localities at Shizitan spanning in time from the LGM through the Younger Dryas give unique insight into ornament usage during this time period of significant climate changes not represented by other sites. This study serves as a descriptive introduction to the characteristics of the Shizitan ornaments and trends in their production and usage over time, which we divide into four distinct phases representing changes in hunter–gatherer choices and preferences in the use of these symbolic objects. This initial presentation may lead to further experimental and comparative studies and raise awareness of the potential of the North China dataset in understanding Late Paleolithic behavior and adaptations.

Late Paleolithic sites in North China have long been known to produce forms of personal ornamentation other than OES beads. Excavations in 1933–34 at the Zhoukoudian Upper Cave near Beijing revealed burials of eight modern human individuals and pendants of perforated animal teeth, mollusk shell, fishbone, and stone (Li et al, 2018). Although the dating of the Zhoukoudian Upper Cave burials is debated (ranging between 35 and 10 Ka cal BP), Li Feng et al. (2018: 174) note that all other such examples of perforated ornaments in China date after 34 Ka cal BP. Subsequent discoveries of personal ornamentation in China (Li and Huo, 1990; Pei, 1999; Wang et al., 2012; Ma, 2016; Wei et al., 2017; Wei et al., 2017; Li et al, 2018; Wei and Gao, 2020) lead to an overall understanding concerning the origin and development of ornaments made of freshwater and marine mollusk shell, OES, bone, teeth, stone, and other materials in the Late Paleolithic period. Research over the past decade on OES ornaments has focused on three sites because they have undergone controlled excavations, namely, Shizitan (Song et al., 2011; Song and Shi, 2013a; Song and Shi, 2013b), Shuidonggou (Wang et al., 2009; Wang, 2010; Wang et al., 2011; Wei et al., 2017), and Yujiagou (Nihewan Basin) (Wang et al., 2020). This work has included studies on the origins of OES products, manufacturing techniques and sequences (Song and Shi, 2013a; Song and Shi, 2013b), and related experimental archaeology (Wei et al., 2017; Wei and Gao, 2020) and follows upon previous such work carried out primarily on materials from African sites (e.g., Kandel and Conard, 2005; Orton, 2008; Miller and Willoughby, 2014; Collins and Steele, 2017; Werner and Miller, 2018; Craig et al., 2020).

MATERIALS AND METHODS

This descriptive study is based on observations and measurement of the Shizitan site data set of OES ornaments, the purpose of which is to introduce initial observations and hypotheses concerning diachronic changes in the production and display of these objects. Characterizations of technology (e.g., cutting, drilling, polishing, and color alteration) and usewear are derived from sources cited below that present experimental studies on OES and observations of archaeological objects. Classification, measurements, and observations of color alteration for 41 pieces

TABLE 1 | OES ornament counts, contexts, and associated radiocarbon dating at Shizitan localities.

Locality	Layer	Lab no	14C sample materials	Dates[a]	OES pendants	OES beads			Total	References
						Finished	Semi-finished	Fragments		
SZT9	Layer 4	—	Charcoal	12,756–11,350	—	2	4	5	11	Shizitan Archaeological Team, (2010)
SZT12G	—	BA121964	Burnt bone	15,987–15,394 (95.4%)	—	1	—	—	1	Unpublished
SZT1	Lower cultural layer	—	Bone	35,100–17,000	—	—	—	2	2	Yuan et al. (1998)
SZT24	—	BA04008	Bone	20,460–19,960 (95.4%)	1	—	—	—	1	Song and Shi. (2013a), Song and Shi. (2013b)
SZT29	Layer 2	BA101414	Bone	18,059–17,505 (95.4%)	—	2	—	—	26	Song et al. (2017)
	Layer 7 Upper contact	—	Charcoal and burnt bone	Later stage of 26,000–24,000	—	1	—	—	—	—
	Layer 7 Top	—	—	—	—	4	—	—	—	—
	Layer 7 spits 5–2	—	—	Early stage of 26,000–24,000	19	—	—	—	—	—
Total	—	—	—	—	20	10	4	7	41	—

[a]*Notes: Date ranges without lab numbers are estimated based on multiple, calibrated AMS. ^{14}C dates from the same layer. Shizitan 1 dating is a broad estimate. The SZT12G date may not be reliable: we estimate this layer to date later, roughly contemporaneous with SZT9 layers 4–5.*

of OES ornaments (categorized as pendants or beads), blanks, and raw material from five localities of the Shizitan site (SZT 29, 24, 1, 12G, and 9) and seven distinct stratigraphic contexts within them (described separately below) are tabulated for the purpose of determining potential trends in changes in ornament size, production, function, use, and preference over a 15,000 year period from the Last Glacial Maximum through the Younger Dryas (see **Tables 1**, **2**). For details on previous studies of Shizitan OES ornament production and usewear, including experimental studies, see Song and Shi (2013a), Song and Shi (2013b).

Classification

Most of the OES materials from the Shizitan localities are finished products (with the exception of blanks and raw material from Shizitan 9 during the last phase of occupation of Shizitan). We classify these objects with central apertures for stringing into "beads" and "pendants." This classification, which size classes also align with (pendants tend to be larger), is based primarily on evidence for the stringing or suspension technique, observed through usewear and experiment in previous studies (Song and Shi 2013a; Song and Shi, 2013b). The OES products classified as pendants have usewear on one quadrant of the ornament's OES exterior and interior faces left from individually tying the ornament with a knot or hitch there so that they would be suspended at what then becomes the top of the pendant: this also leaves the exterior or interior shell surface "face" of the object maximally visible (Song and Shi, 2013a). Beads are objects with a central perforation (bead hole) and lack this sort of usewear. Beads were likely strung in groups, with stringing penetrating through the central holes of a set of ornaments, in which case the flat interior or exterior OES surface would not be as visible as with strung pendants.

Measurement

Measurements were made for external diameter, aperture diameter, "body width", and thickness. We define "body width" as the distance from the hole wall to the exterior edge of the ornament. Because the ornaments' outer circumference and aperture (central perforation) are not perfectly round, either because of how they were manufactured or due to uneven usewear, the measurements given in **Tables 1**, **2** are averages, made as follows: for beads, four body width measurements were taken, once every 90° around the object, and the average is used; the aperture diameter is the average of four measurements, each every 45°. For pendants, which we define as ornaments suspended from their upper part, because there is heavy usewear on almost all of them from stringing and polishing causing loss of the body diameter from top to bottom and widening of the aperture from wear at the top of the hole wall (from where the pendant had been suspended by stringing), the body width measurements are an average of two values, measured at 90 and 270° around the diameter, and the aperture diameter is measured across this same line.

Color and Heating

Color is observed by naked eye and indicated using general terminology. Based on previous studies of OES heat treatment and post-depositional changes cited below, we infer that color changes were brought about primarily by heat treatment, likely due to exposure to open fire, which is also supported by observations of surface changes such as crackling, but this must be tested and experimented further across all OES data sets as the particular processes by which some color changes occur still remain unknown, such as for the black color found at Shizitan (Collins and Steele, 2017). For Shizitan, a series of

TABLE 2 | Measurements (in mm) of the OES ornaments from Shizitan site localities SZT29, 24, 12G, and 9. Body width (BW) = distance from the hole wall to exterior edge.

Locality	Object no. or context	Depth below site datum (cm)	External diameter	Aperture diameter (AD)	Body width (BW)	BW/ AD	Thickness	Notes	Type	Color	Notes
SZT9 Layer 4	Spit 2	250–255	3.43	—	—	—	2.2	Fragment	Bead	Ivory	**Figure 2**: 7; **Figure 5**: 9
	Spit 3	255–260	4.29	1.31	1.4	1.07	2.10	Two-sided perforated	Bead	Ivory	**Figure 2**: 1; **Figure 5**: 1
	Spit 4	260–268	5.67	1.23	—	—	2.10	One-sided drilling	Bead	Ivory	**Figure 2**: 4; **Figure 5**: 4
	Spit 5	268–274	3.80	1.14	1.4	1.23	2.05	Two-sided perforated	Bead	Ivory	**Figure 2**: 2; **Figure 5**: 2
	Spit 6	274–280	5.67	0.99	—	—	2.10	Two-sided drilling	Bead	Ivory	**Figure 2**: 3; **Figure 5**: 3
	Spit 10	295–305	6.40	1.38	—	—	1.20	Burnt fragment, one-sided drilling	Bead	Black	**Figure 2**: 6; **Figure 5**: 5
	Spit 10	295–305	4.07	—	—	—	2.03	Fragment	Bead	Ivory	**Figure 2**: 8; **Figure. 5**: 11
	Spit 11	305–310	4.92	1.48	—	—	2.10	One-sided drilling	Bead	Ivory	**Figure 2**: 5; **Figure 5**: 6
	Spit 11	305–310	5.33	—	—	—	2.62	Fragment	Bead	Ivory	**Figure 2**: 9; **Figure 5**: 8
	Spit 12	310–316	4.34	—	—	—	2.3	Fragment	Bead	Ivory	**Figure. 2**: 10; **Figure 5**: 10
	Spit 14	323–330	6.02	—	—	—	1.9	Fragment	Bead	Ivory	**Figure 2**: 11; **Figure 5**: 7
—	Mean	—	4.05	1.23	1.4	1.15	2.08	Includes only perforated ones	—	—	—
SZT12G	1853	124.9	5.57	2.12	1.7	0.80	2.13	Used	Bead	Ivory	**Figure 2**: 12; **Figure 4**: 1
SZT24	307	48.6	9.43	2.61	—	—	1.31	Used	Pendant	Ivory	**Figure 2**: 13; **Figure 3**: 20
SZT29 Layer 2	1836	162	7.46	2.89	2.1	0.73	2.01	Used	Bead	Ivory	**Figure 2**: 14; **Figure 4**: 3
	13,864	Collected	8.74	4.01	2.4	0.60	1.70	Used	Bead	Ivory	**Figure 2**: 15; **Figure 4**: 2
—	Mean	—	8.1	3.45	2.25	0.67	1.86	—	—	—	—
SZT29 Layer 7 Upper Contact	72–76	1,145–1,150	7.57	3.4	2.4	0.71	1.81	Remnant half	Bead	Ivory	**Figure 2**: 16; **Figure 4**: 4
SZT29Layer 7 Spits 2–1[a]	13846	1,147–1,154	5.71	2.60	1.6	0.62	1.36	Used	Bead	Ivory	**Figure 2**: 19; **Figure 4**: 5
	13847	1,147–1,154	5.41	2.70	1.3	0.48	1.29	Used	Bead	Ivory	**Figure 2**: 20; **Figure 4**: 6
	1348	1,147–1,154	5.39	2.67	1.4	0.52	0.98	Used	Bead	Ivory	**Figure 2**: 18; **Figure 4**: 7
	70–92	1,189–1,190	5.55	2.88	1.2	0.42	1.30	Used	Bead	Ivory	**Figure 2**: 17; **Figure 4**: 8
—	Mean	—	5.52	2.71	1.38	0.51	1.23	—	—	—	—
SZT29 Layer 7 Spits 5–2	13,849	1,149–1,170	12.64	2.22	5.3	2.39	1.53	Used	Pendant	Black	**Figure 2**: 21; **Figure 3**: 1
	13850	1,159.5	10.12	2.85	3.6	1.26	1.69	Used	Pendant	Black	**Figure 2**: 22; **Figure 3**: 14
	13852	1,150–1,170	9.30	—	—	—	1.43	Fragment, used	Pendant	Black	**Figure 2**: 23; **Figure 3**: 3
	64–97	1,150–1,170	11.43	—	—	—	1.8	Fragment, used	Pendant	Black	**Figure 2**: 36; **Figure 3**: 19
	66–106	1,170–1,180	11.13	—	—	—	1.89	Fragment, used	Pendant	Gray	**Figure 2**: 38; **Figure 3**: 16
	13851	1,170–1,180	10.37	3.79	3.6	**0**.91	1.72	Used	Pendant	Black and Gray	**Figure 2**: 24; **Figure 3**: 4
	13853	1,180–1,190	10.89	2.89	3.7	1.28	1.96	Used	Pendant	Black	**Figure 2**: 25; **Figure 3**: 5
	13854	1,180–1,190	11.47	2.73	4.5	1.65	1.89	Used	Pendant	Black	**Figure 2**: 26; **Figure 3**: 6

(Continued on following page)

TABLE 2 | (*Continued*) Measurements (in mm) of the OES ornaments from Shizitan site localities SZT29, 24, 12G, and 9. Body width (BW) = distance from the hole wall to exterior edge.

Locality	Object no. or context	Depth below site datum (cm)	External diameter	Aperture diameter (AD)	Body width (BW)	BW/ AD	Thickness	Notes	Type	Color	Notes
	13855	1,180–1,190	10.86	2.95	4.0	1.36	1.69	Used	Pendant	Black	**Figure 2**: 27; **Figure 3**: 2
	13856	1,180–1,190	12.13	2.94	4.5	1.53	2.08	Used	Pendant	Black and Gray	**Figure 2**: 28; **Figure 3**: 8
	13857	1,180–1,190	12.25	3.11	4.4	1.41	2.05	Used	Pendant	Gray	**Figure 2**: 29; **Figure 3**: 9
	80–103	1,180–1,190	9.82	—	—	—	1.7	Fragment, used	Pendant	Black	**Figure 2**: 39; **Figure 3**: 17
	81–109	1,180–1,190	7.46	—	—	—	1.57	Fragment, used	Pendant	Black	**Figure 2**: 37; **Figure 3**: 18
	13858	1,200–1,210	12.54	—	—	—	2.13	Fragment, used	Pendant	Black	**Figure 2**: 30; **Figure 3**: 10
	13859	1,200–1,210	9.82	—	—	—	2.02	Fragment, Used	Pendant	Gray	**Figure 2**: 31; **Figure 3**: 11
	13860	1,210–1,220	11.13	2.03	4.7	2.32	2.29	Used	Pendant	Black and gray	**Figure 2**: 32; **Figure 3**: 12
	13861	1,210–1,220	12.88	2.91	5.1	1.75	1.85	Used	Pendant	Black	**Figure 2**: 33; **Figure 3**: 13
	13862	1,210–1,220	11.28	2.94	4.3	1.46	1.75	Used	Pendant	Black and gray	**Figure 2**: 34; **Figure 3**: 7
	13863	1,210–1,220	10.52	—	—	—	0.56	Fragment, used	Pendant	Black	**Figure 2**: 35; **Figure 3**: 15
—	Mean	—	11.46	2.85	—	1.57	1.86	Fragments not included	—	—	—

[a]*Note: The beads in SZT29 Layer 7 Spits 2-1 were over-drilled, meaning the conchoidal hole opening extended through the bead edge, which causes loss of the OES's original thickness.*

planned experiments are ongoing to verify particular color changes in OES under different conditions (heat from flame vs. boiling, tracking time and temperature).

SHIZITAN SITE ARCHAEOLOGICAL CONTEXTS

The Shizitan site is composed of at least 30 open-air site localities located along the present-day Qingshui River (a perennial tributary of the Yellow River), in Jixian County, Shanxi Province, on the North China Loess Plateau (**Figure 1**). First discovered in 1980, and with several localities excavated between 2000 and 2010, the sequence for the site, ranging from ca. 30 to 8.5 Ka cal BP, is best represented at excavated localities SZT29 and SZT9, which have contexts extending from before and during the Last Glacial Maximum (LGM) and through the Younger Dryas (YD) into the Early Holocene, with correlating changes in their Late Paleolithic material cultural records (Shizitan Archaeological Team, 2010; Song et al., 2017; Song et al., 2019).

Late Paleolithic remains at Shizitan include more than 300 hearths and tens-of-thousands of artifacts, including lithics, grinding slabs and handstones (Liu et al., 2011; Liu et al., 2013), ochre pigments, polished bone needles (Song et al., 2016), and ornaments made of bivalve shell and ostrich eggshell. The localities provide a record of human adaptations to the challenging local conditions of the Loess Plateau through the Last Glacial period, including the LGM (when microblade production begins) and YD.

Here, we discuss the forty-one pieces of identified ostrich eggshell from five localities, SZT1, SZT9, SZT12G, SZT24, and SZT29 (**Figure 1**). Counts and dating based on calibrated radiocarbon dates from cultural layers at the localities are provided in **Table 1**.

Shizitan 29

Shizitan locality 29 (36°2′54″N, 110°35′22″E, 723 masl) is located about 500 m east of Shizihe Village of Jixian County. It was excavated from 2009 to 2010. The 1,200 m^2 excavation area features a 15 m deep depositional sequence with eight "cultural layers" (Level 8 is the lowest, dating ca. 28 Ka cal BP) typically interspersed with geological layers with few artifacts and no evidence of anthropogenic inputs. It is an open-air site thought to be ephemerally but repeatedly occupied by hunter–gatherers over its history. A total of 285 hearths were excavated in Layers 1 through 7 (Song et al., 2017; School of History and Culture, Shanxi University and Shanxi Provincial Institute of Archaeology, 2017). Among more than 80,000 artifacts, 26 OES ornaments were excavated in Layers 7 (**Figures 2**: 16–39) and 2 (**Figure 2**: 14, 15), including six identified after the reports in 2013 and 2017 (Song and Shi, 2013a; Song and Shi, 2013b; Song, 2013; Song et al., 2017) (**Figure 2**: 16, 17, 36–39).

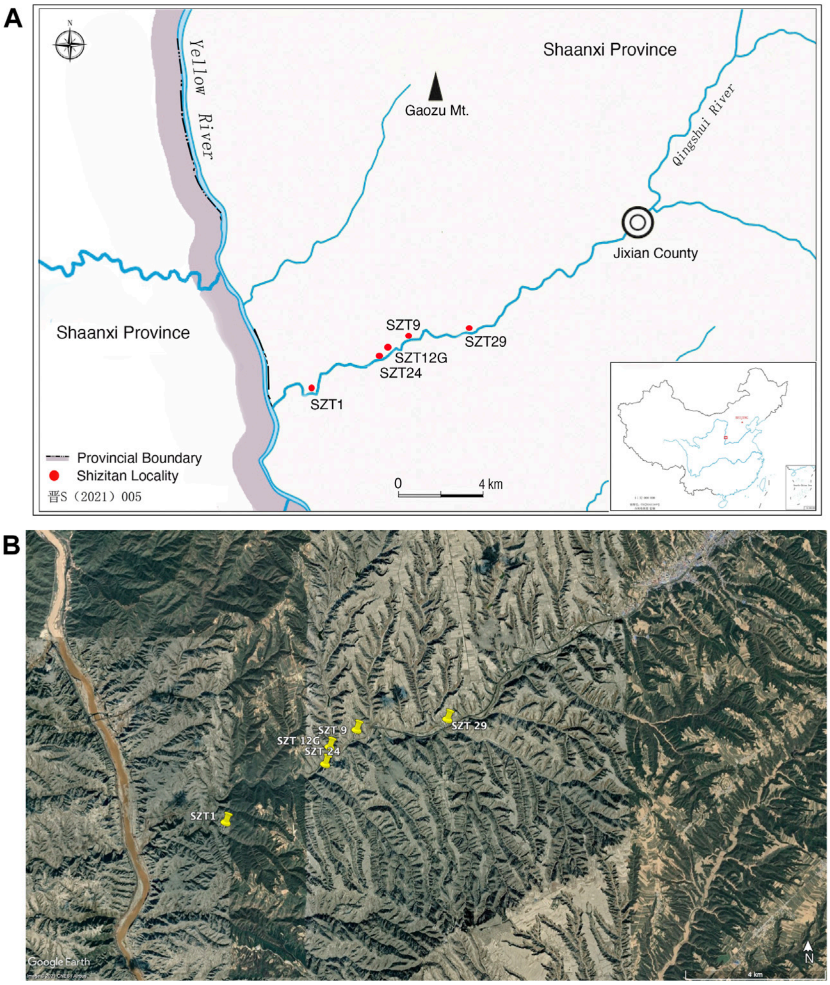

FIGURE 1 | (A) Map showing the locations of the excavated Shizitan localities with OES ornaments, along the Qingshui River, Shanxi Province. **(B)** Google Earth satellite image showing the positions of the Shizitan localities within the Loess Plateau landscape.

The earliest OES ornaments at SZT29 are found in Layer 7, dating between ca. 26–24 Ka cal BP. Layer 7 reflects the onset of colder and drier conditions during the LGM (Song et al., 2017). Song et al. (2019) divide Layer 7 into two stratigraphical sampling units based on the excavated 10 cm spits in order to investigate a major lithic technological change: "Layer 7 Base" represents the earlier "advanced core and flake industry" in spits 7–12 that continued from Layer 8, and "Layer 7 Top" represents spits 1–2, where microblade production replaces the earlier core and flake industry (and is one of the earlier true microblade pressure productions in North China) (Song et al., 2019). The earliest OES pendants at SZT29 appear in Layer 7 Spits 5–2: it is not clear if they appear before a limited amount of microblade technology is present at the site. In spits 1–2, however, the earliest OES beads are found in what is clearly the first microblade industry context.

Layer 7 Spits 5–2, as shown in **Table 1**, produced 19 perforated OES items identifiable as personal ornamentation (**Figure 2**: 21–39; **Figure 3**: 1–19). Measurement data excludes eight broken/partial pieces. The average diameter of the perforated pieces is 11.46 (9.3–12.88) mm, thickness 1.86 (1.43–2.29) mm, and aperture diameter 2.85 (2.03–3.79) mm (**Table 2**). In this study, the term "perforating" is used generally to refer to purposefully working a hole through the item as a stage in the manufacturing process. Where evidence indicates that an aperture was made though drilling, we specifically mention this. Werner and Miller (2018), in their study of drilling techniques, distinguish perforating (which would include holes made by pecking, gouging, or punching) from rotary drilling, which is actually the technique used on the vast majority of African Stone Age OES beads they observed. We suggest the same may hold for North China OES, but further observation and experimentation are needed that are outside the scope of this initial, descriptive study.

The ornaments from Layer 7 Spits 5–2, thus, show relative uniformity in size, and they are the largest-sized examples of OES ornaments across all Shizitan localities. An important trait of these 19 ornaments is their color. Their black gray or half black/

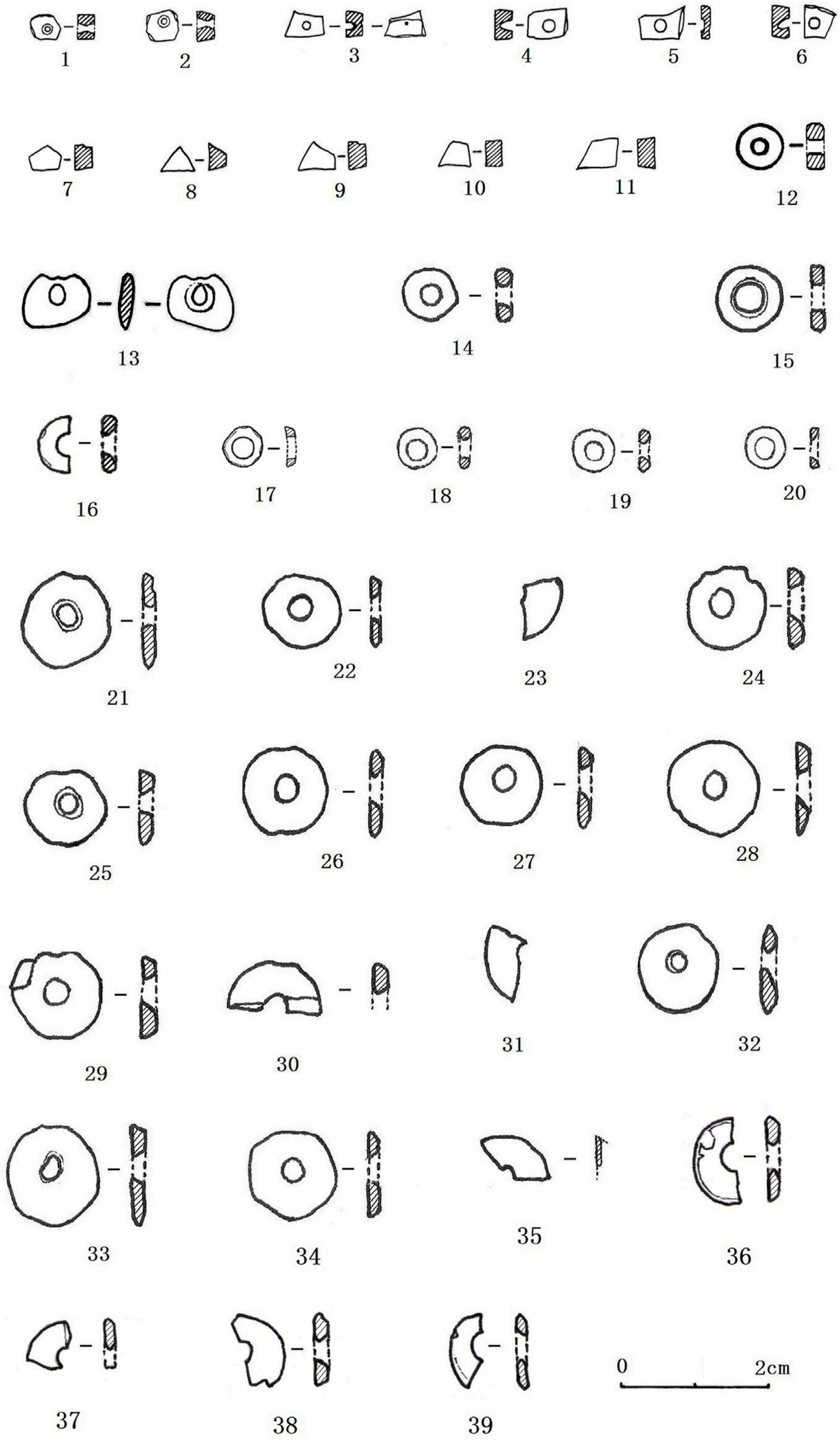

FIGURE 2 | Perforated OES ornaments identified at localities of the Late Paleolithic Shizitan site. 1, 2. Perforated beads from SZT9 Layer 4; 3–6. Semi-perforated beads from SZT9 Layer 4; 7–11. Broken pieces from SZT9 Layer 4; 12. Used bead from SZT12G; 13. Heavily used pendant from SZT24; 14–15. Used beads from SZT29 Layer 2; 16. Used bead from SZT29, Layer 7 upper contact; 17–20. Used beads from SZT29 Layer 7 Spits 2–1; 21–39. Used pendants from SZT29 Layer 7 Spits 5–2.

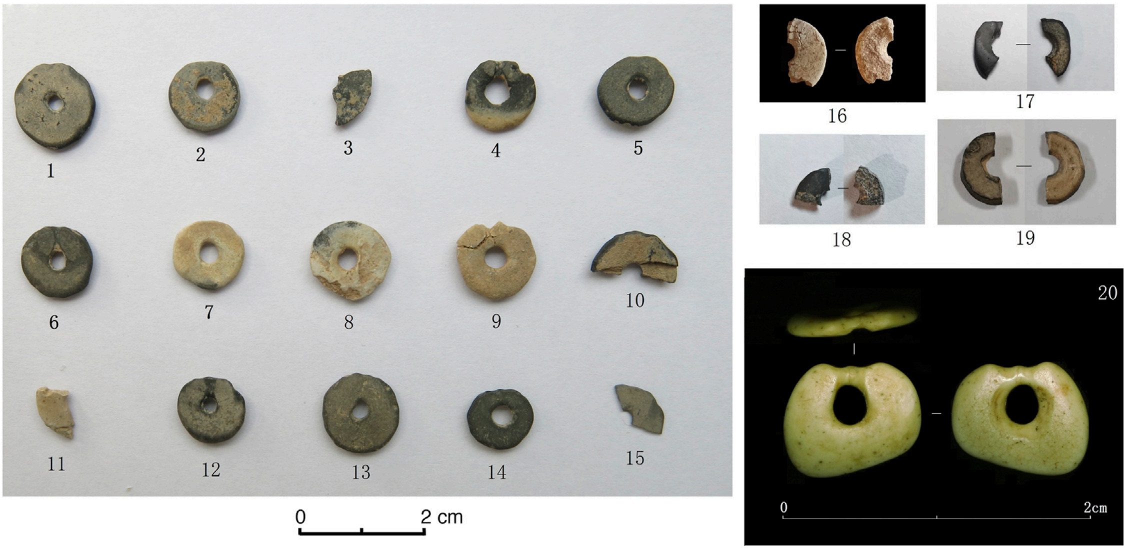

FIGURE 3 | Perforated OES pendants and pendant fragments from Shizitan SZT29 Layer 7 Spits 5-2 and SZT24. 1–19 are to the same 2 cm scale. 1–15. Pendants with usewear from SZT29 Layer 7 Spits 5–2, exterior surfaces; 16–19. Exterior surface **(left)** and interior surface **(right)** of pendants with use wear from SZT29 Layer 7 Spits 5-2; 20. SZT24, pendant top, exterior, and interior, showing heavy usewear. Scales are 2 cm in length.

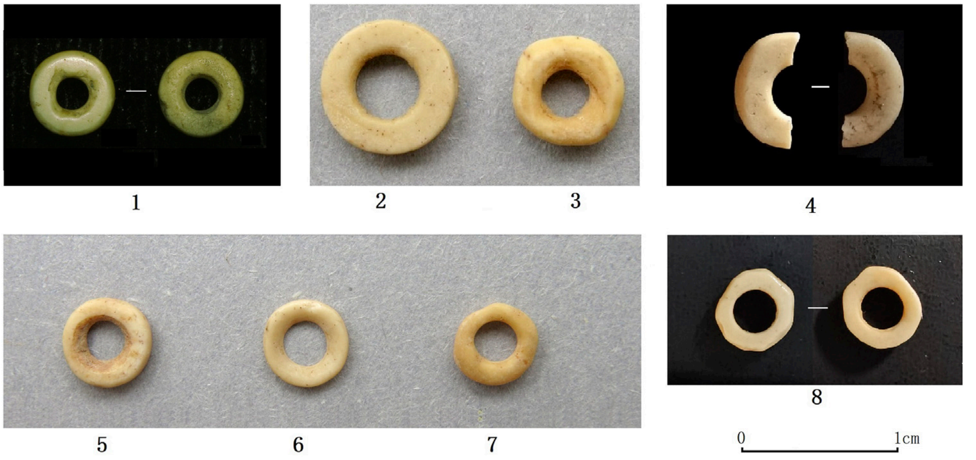

FIGURE 4 | Perforated OES beads from SZT29 Layer 7 Spits 2–1, SZT29 Layer 7 upper contact, SZT29 Layer 2, and SZT12G, all to the same scale. 1. Used bead from SZY12G (exterior and interior views); 2–3. Two used beads from SZT29 Layer 2 (exteriors); 4. Broken bead from SZT29 Layer 7 upper contact (exterior and interior); 5–8. Four used beads from SZT29 Layer 7 Spits 2–1: 5-6. Interior; 7. Exterior; 8. Exterior **(left)** and interior **(right)**.

half gray coloring is inferred to be indicative of burning, and some of these also feature surface crackling. However, the particular process by which they can become this color remains unknown despite actualistic studies. For example, Collins and Steele (2017) note that no experimental studies of heating using ovens or kilns has been able to reproduce black OES but suggest that oxygen availability and the introduction of organics need to be considered.

Those ornaments that show heavy usewear have an enlarged aperture diameter and lesser average thickness than those with no significant wear: this is also a phenomenon observed by Orton (2008: Figure 7), who attributes finding larger holes in finished beads than in unfinished ones to wear. One noteworthy form of wear on the Layer 7 Spits 5–2 ornaments is a pattern of abrasion on a particular part of the surface which previous studies indicate is the result of long-term usage of the ornaments as strung items (Song and Shi, 2013a; Song and Shi, 2013b). These studies determined that the abrasion patterns on the objects indicate that these early examples were worn as pendants (rather than beads strung together): this is ascertained by dark markings at the top of the pendant indicative of stringing being tied to suspend the ornament from the top (rather than from its center as a bead), and heavier wear at the bottom, outer surface (see Song and Shi, 2013a: Figure 3).

In SZT29 Layer 7 Spits 2–1, a total of 5 OES ornaments were unearthed. These ornaments show significant differences from the earlier examples. First, they are smaller in size than the ones from Layer 7 Spits 5–2. Their coloring is different, as well, being ivory in color and lacking indications of being burnt. In total, 4 of the 5 ornaments (**Figure 2**: 17–20; **Figure 4**: 5–8) are decidedly smaller in size but with a bigger hole: their average diameter is 5.52 (5.39–5.71) mm and the aperture diameter is 2.71 (2.60–2.88) mm. The larger drilling not only magnified the aperture diameter and decreased the average thickness to 1.23 (0.98–1.36) mm (**Table 2**) but also made these four ornaments somewhat irregular in shape, especially their outer contour, even though they were heavily polished all over. The fifth ornament (SZT29:72–96; **Figure 2**: 16; **Figure 4**: 4) from Layer 7 Spits 2–1 looks more circular, regular, and bigger than the other four beads, although the piece is partial, with a residual length of 7.57 mm. The clearly visible cross section features a very glossy hole wall with a very steep and polished edge, indicating that this was one of a string of beads. Ochre pigment residues were also visible on its surface.

SZT29 Layer 2 (ca. 19–18 Ka cal BP) marks the end of LGM conditions. In traditional morphological typological terms, the microblade technology had already shifted from semi-conical to boat-shaped microcores in the early spits of Layer 6, and these continued through Layer 2 (but see Song et al., 2019, for problems with the traditional lithics approach). Only two OES ornaments (**Figure 2**: 14, 15; **Figure 4**: 2, 3) were found in Layer 2 deposits: one (S29:1836; **Figure 2**: 14; **Figure 4**: 3) was excavated near a hearth, and the other was recovered through sieving of fill from the top of the layer. Compared to S29:72–96 from Layer 7 Top, the excavated Layer 2 ornament had a steeper and more polished hole wall but had a sub-regular round shape with the diameter 7.46, aperture diameter 2.89, and thickness of 2.01 mm; the sieved one was perfectly shaped into a regular, circular ring of diameter 8.74, aperture diameter 4.01, and thickness 1.7 mm (**Table 2**). Polish and ochre pigments could be observed on their surfaces.

Shizitan Locality 24

Locality 24 (36°2′12″N, 110°33′1″E) is located 1 km west of Gaolouhe Village. It was excavated in 2005. The 21 m^2 excavation area features ca. 0.5 m thick deposits covered by slope wash. About 1,000 lithic artifacts and animal bones, along with one OES bead, were unearthed. The site report has not been published. One AMS ^{14}C determination on animal bone is available, with a date of 20,460–19,960 cal BP (95.4%). The author SYH took part in the excavation and observed the OES bead (see Song and Shi, 2013a; Song and Shi, 2013b) (**Figure 2**: 13; **Figure 3**: 20). It measures 9.43 mm in diameter, 2.61 mm in aperture diameter, and 1.31 mm in thickness (**Table 2**). It shows indications of long-term usage, with abrasion and polish so heavy that its original shape could not be distinguished. However, due to this heavy usewear, we are able to determine that this ornament used the same stringing and tying fashion as the OES ornaments in SZT29 Layer 7 Spits 5–2 (**Figure 3**). Therefore, we can ascertain its usage as an originally ring-shaped pendant.

Shizitan Locality 1

Locality 1 (36°1′17.9″N, 110°31′7.11″E) is the westernmost and first excavated locality of the Shizitan site. It is located in fluvial deposits along the Qingshui River, 2 km southwest of Xialing Village, Jixian County. It was excavated in 1980, but methodology at that time simply divided the artifacts from all contexts into two periods, early and late (Linfen Administrative Bureau of Culture, 1989). Estimated dating ranges were 35.1–17 ka BP (Yuan et al., 1998; Xia et al., 2001). Two broken pieces of OES were unearthed together with 12 lithic artifacts with rough retouch. Observations of the OES surfaces revealed no signs of retouch or usewear, but there was apparent rounding at the shells' edges, which we attribute to fluvial transport.

Shizitan Locality 12G

Locality 12G (36°2′28″N, 110°33′6″E, 668 masl) is located 500 m west of Gaolouhe Village. It was excavated in 2005. The 6 m^2 excavation area features deposits 1.9 m deep. One radiocarbon date of ca. 15.5 Ka cal BP (**Table 1**), according to the dating laboratory, may be unreliable due to the condition of the bone sample: based on the artifact assemblage and geology of the deposits, we believe this locality dates later, roughly contemporaneous with SZT9 Layers 5 and 4. More than 1,700 artifacts were distributed throughout the deposits, including lithics, animal bone, and burnt bone (Shizitan Archaeological Team, 2013). The microblade technology can be characterized in traditional morphological terms by a single type of wedge-shaped microcore. Only one small, perforated OES ornament (S12G: 1853; **Figure 2**: 12; **Figure 4**: 1) was found and represents the artistic achievement of its time. This OES bead has usewear and is more regular in shape with a circular outline, center hole, and steep hole wall. It measures 5.57 mm in diameter, 2.12 mm in aperture diameter, and 2.13 mm in thickness (**Table 2**), which is smaller than those in SZT29 Layer 2 dating to ca.18 Ka cal BP.

Shizitan Locality 9

Locality 9 (36°02′44″N, 110°33′37″E, 688 ± 5 masl) is located about 150 m north of Gaolouhe Village in Jixian County. It was identified in 2000 and excavated over three seasons in 2001, 2002, and 2005 (Shizitan Archaeological Team, 2010; School of History and CultureShanxi University and Shanxi Provincial Institute of Archaeology, 2017). Nine AMS ^{14}C dates indicate the locality ranges across the YD and into the Early Holocene, which is the time period in the lowland North China Plain of the transition to sedentism, food production, and the Early Neolithic period (but not yet in the Loess Plateau). The excavated area reached 25 m^2 with deposits 4.55 m in depth composed primarily of aeolian loess. These can be divided into five cultural layers. A total of 2,359 screened artifacts and an additional 5,000 sieved pieces (primarily lithic artifacts and animal bones) were recovered from all layers except Layer 2. Burnt and broken animal bone indicates the general use of fire at locality 9 in all layers, and it is specifically indicated by a hearth in Layer 3. All of the examples of grinding stones, pigments, and ornaments made of mollusk shell and OES (Song et al., 2011; Song and Shi, 2013a; Song and Shi, 2013b) are found only in Layer 4, dating ca. 12,756–11,350 cal BP, which falls into the Younger Dryas period of climatic downturn (**Table 2**). A

FIGURE 5 | Perforated OES beads (top), preforms (rows 2, 3), and blanks (bottom row) from Shizitan SZT9. Row 1. Perforated pieces; Row 2. Bi-directionally drilled piece; Row 3. Uni-directionally drilled pieces; Row 4. Blanks or remnant pieces. Scale is 1 cm.

total of 11 pieces of OES were sieved from Layer 4. These include two perforated pieces (**Figure 2**: 1, 2; **Figure 5**: 1, 2), three pieces with uni-directional drilling (**Figure 2**: 4–6; **Figure 5**: 4–6), one piece with bi-directional drilling (**Figure 2**: 3; **Figure 5**: 3), and five blanks or remnant pieces (**Figure 2**: 7–11; **Figure 5**: 7–11). These allow understanding of the procedures for creating beads, from blank and preform preparation, to perforation or one- or two-sided drilling, to final finishing. Completed pieces average 4.05 mm in diameter, 1.23 mm in aperture diameter, and 2.08 mm in thickness (**Table 2**). The completed beads are not so regular in shape and have no usewear on their surfaces.

NON-EDIBLE EXPLOITATION AND UTILIZATION OF OSTRICH EGGSHELL

Ostrich eggs, as the largest of avian eggs, and with hard shells, can provide not only a high level of protein, fat, and calories (Collins and Steele, 2017) but also offer a raw material for non-edible products. Although whole ostrich eggs potentially could have served as a food source of great nutritional value, we have no direct evidence for the human consumption of ostrich eggs at Paleolithic sites in China. There are some reports of intact ostrich eggs being found *in situ* in northern China, but because they are still whole, they were never consumed or used by humans. Although it is difficult to ascertain if ostrich eggs had been used as a food source, generally speaking, ostrich eggs must not have signs of hatching if people acquired them for food. Hatched OES potentially leaves indicators on the exterior and interior surfaces that can be seen microscopically: the outer surface of an incubated eggshell will show fissures associated with the cuticle overlying the pore canals, and the interior surface can show dissolved mammillary cones (a calcium reservoir for embryo bone building) (Board, 1982; Dauphin et al., 2006; Wang et al., 2020). Nevertheless, good evidence for ostrich egg food consumption remains elusive.

Instead, we only have evidence of ostrich eggshell usage for non-edible purposes. In South Africa, in addition to OES personal ornamentation, OES water flasks with engraved designs are found, such as at Diepkloof Rock Shelter (Texier et al., 2013) in Middle Stone Age contexts as early as 60 ka BP. There are also other pieces with engraved geometric motifs dating possibly as early as ca. 109 ka BP. Other early, engraved OES with abstract designs are found in the Howiesons Poort Industry at Klipdrift Shelter, similarly dated ca. 66–59 ka BP (Henshilwood et al., 2014).

In China, evidence only exists for OES used as ornaments. Interestingly, observations of the OES ornaments at Shizitan indicate that in nearly all of the ornaments or by-production pieces (except those with heavy usewear that altered the surfaces), the dissolved tips of mammillary cones are visible on the interior sides. This indicates that for the Shizitan ornaments, hunter–gatherers were collecting shell from *hatched* ostrich eggs to manufacture the objects (**Figure 6**).

DIACHRONIC CHANGE IN THE UTILIZATION OF OES AT SHIZITAN

The Shizitan localities provide a localized record of diachronic change in OES ornament production and usage from the Last Glacial Maximum through Terminal Pleistocene. Controlled stratigraphic excavations with radiocarbon dated sequences allow us to place changes in the OES ornament typology and hypothesized function into changing environmental and cultural/technological contexts, leading to insights into the potential roles these objects played. We can divide the diachronic changes in the production and usage of OES ornaments at Shizitan into four phases.

Phase 1 is found in Layer 7 Spits 5–2 at Shizitan 29 and would date to an earlier part of the date range of ca. 26–24 Ka cal BP for Layer 7. The earliest OES ornaments at the site appear as pendants in this layer, as is determined by usewear from them being individually tied with a string through the hole and wrapping one perimeter edge at what then becomes the pendant's top (Song and Shi, 2013a; Song and Shi, 2013b). A total of 19 perforated OES ornaments are identified for this phase. These early pendants are larger than all subsequent OES ornaments: they are bigger in average diameter (11.46 mm) and have a smaller average aperture diameter (2.85 mm). This means that the display area of the surface of the ornaments is much greater than in later periods. Here (see **Table 2**), we compare the display area using the ratio of the "body width" (meaning the measurement from the hole wall to the outer edge) of the beads to the "aperture diameter" (BW/AD) to express the display area, which for 11 ornaments in Layer 7 Spits 5–2 averages 1.57 (subsequent phases range 0.51–1.15). The larger size and large display area of the earliest OES ornaments are visualized in

FIGURE 6 | Interior surfaces of OES fragments from Shizitan 9 Layer 4 at ×500 magnification. **(A)**. Undrilled fragment recovered by sieving. **(B)**. Fragment with drilling from one side, recovered by sieving. **(C)**. Piece drilled from two sides that was shaped into an irregular circular ornament; recovered by sieving. **(A, B)** show dissolved tips of mammillary cones and exposed pore canals indicative of humans at Shizitan acquiring OES raw material from eggs that had incubated and hatched. On **(C)**, parallel striations are visible indicating that completed beads are polished during a final step in their manufacture, and this obscures the mammillary cones.

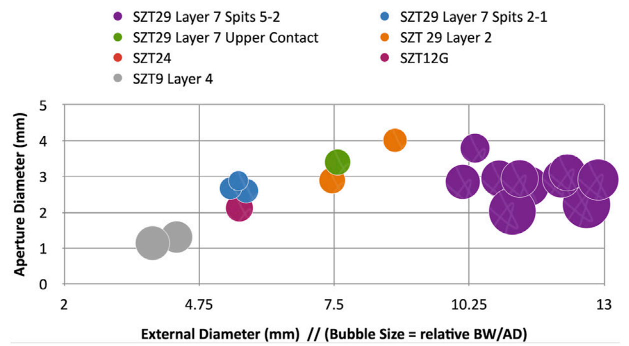

FIGURE 7 | Bubble chart plotting three variables to visually compare Shizitan OES ornament data: external diameter (mm; x-axis), aperture diameter (mm; y-axis), and the relative "display area" (body width/aperture diameter ratio), indicated by the size of the bubble. Colors indicate Shizitan contexts. Plotted ornaments must have all three values available; see **Table 2** for values. Note the large display area (bubble size) despite the small external diameter for the latest (Phase 4) ornaments, from SZT 9.

the bubble chart in **Figure 7**. Also it is noted that unlike later ornaments, the Phase 1 OES pendants are seemingly burnt, as indicated by gray and/or black coloration, although the heating process that may turn OES this coloration remains unknown (Collins and Steele 2017). They are finished products with signs of use. Their appearance in Layer 7 Spits 5–2 means they are present at the site before microblade technology is fully established (Song et al., 2019).

Shizitan 29 Layer 7 Spits 2–1 represents Phase 2, which would date to the later stage of the date range ca. 26–24 Ka cal BP. Phase 2 is represented by a new type of OES ornament (beads), smaller in size than the Phase 1 pendants. Four small OES beads were recovered from sieving of excavated fill from around a series of hearths in the Layer 7 spits 2–1. Although the four beads are from contexts scattered around the hearths, the beads bore no signs of purposeful coloration change. Interestingly, the Phase 2 change to beads is also when microblade technology is established at the site (Song et al., 2019). In some examples, over-drilling has removed the natural outer or inner surface of the OES because the external diameter of the hole reaches the full diameter of the bead on one side. This may mean that an objective in these beads' production was to systematically create beads with regularity in size and section shape (rather than with a shiny, natural surface). The four beads have nearly the same diameter, aperture diameter, and thickness. This uniform size could be an indication that they would be strung in linkage to each other, as beads. Also noteworthy is that they have the smallest BW/AD ratio of 0.51, but the average aperture diameter of 2.71 mm is not much bigger than the ornaments from Phase 1 (these values are visualized together in the **Figure 7** bubble chart).

Phase 3 (ca. 24–16 Ka cal BP) is represented by the use of stylistically larger and heavier-looking OES beads and the use of OES again for pendants. The single pendant from Shizitan 24 shows no great change in size and shape from that of Phase 1, but it does show serious attrition into an irregular quadrangular shape with two very deep striations from strand-wear on the top. The excessive attrition of the original dimensions of the piece renders measurement meaningless. We interpret Phase 3 as a technical extension in pendant manufacture and use from Phase 1 (potentially a continuous tradition but not found at limited Phase 2 excavated localities).

Beads continue to be used in Phase 3 but with some stylistic change. Four OES beads are identified. The earliest one was found in the upper contact of cultural Layer 7 at Shizitan 29 so would perhaps date ca. 24 Ka cal BP. Other examples are found 6,000 years later in Layer 2 in Shizitan 29 and another 2,000 years after that in Shizitan 12G. Even though the measurement of the bead in SZT12G is nearly the same as that in Phase 2, it and the other beads in Phase 3 look bigger and heavier. This appearance is brought about by technical developments and a maturation of techniques oriented toward better visual effect, including smoothing of the surface, rounding of the shapes, and drilling steeper inner walls for the holes. Also noticeable is that the BW/AD ratio increases from 0.62 to 0.8, meaning that the bead hole was becoming relatively smaller and smaller. In addition, pigments can be observed on the beads with the naked eye, especially on the OES interior side, even though the beads had already been rounded through wearing.

During the last phase, Phase 4 (ca. 12.8–11.4 Ka cal BP), eleven OES pieces from Shizitan 9 Layer 4 allow us to observe the local technological process of bead manufacturing. Two of the pieces are completed beads with drilled apertures, while three uni-directionally and one bi-directionally drilled preforms were also recovered, along with five pieces that could be blanks (**Figure 5**); for further discussion of identifying drilling technology, see (Song and Shi, 2013a; Song and Shi, 2013b; Song et al., 2011). The finished beads in Phase 4 are much smaller not only in diameter (3.8 and 4.29 mm) but also in aperture diameter (1.14 and 1.31 mm) (**Figure 7**). Their small external diameter of <5 mm falls into Orton's (2008) range of "small beads." The small aperture raises the BW/AD ratio to 1.15. Song et al. (2011: Figure 5) observe that the aperture diameters of the drilled OES pieces match the size and usewear patterns microscopically observed on recovered microblade pieces that could have served as drilling bits. Concurrent technological improvements in ornament production can also be seen in the perforated shell ornaments from Shizitan 9, for which Song et al. (2011) argue the angle of the hole sections is resultant from microblade drills. These changes correlate with the onset of the climatic downturn of the Younger Dryas. The bead-making record at Shizitan ends at this point. A final stage may be represented by the Shuidonggou site. The Shuiddonggou region was abandoned at the LGM, with human groups not returning until the early Holocene, ca. 10.5 Ka cal BP (Li et al., 2019), when migrating hunter–gatherer groups brought microblade technology and OES bead-making with them: examination of OES beads at Shuidonggou 12 indicates multiple drilling techniques, including twisting drilling and multi-rotary drilling with different kinds of drill bits (Yang et al., 2016).

DISCUSSION

A Shift to Local Ornament-Making

Microscopic examination of the thickness and structure of the OES unearthed at Shizitan indicates that the eggs belong to the most recent but extinct species of North Asian giant ostriches, *Struthio anderssoni* (Lowe, 1931; Yang and Sun, 1960; Zhao et al., 1981; Janz et al., 2009; Song and Shi, 2013a; Song and Shi, 2013b; Yang et al., 2016), which in the Late Pleistocene had a small population distributed across a wide geographical range over the Malan Loess along the Taihang and Zhongtiao Mountain chains in Shanxi, Hebei, and Henan provinces in North China (Young, 1933; An, 1964; Chen, 1985). Although the OES from Layer 7 of Shizitan 29 has a smaller average thickness of 1.86 mm than *S. anderssoni*, it is also smaller than the 1.9 mm average thickness of OES for the smaller, living ostrich, *Struthio camelus* (Lowe, 1931); this is because the shell thickness was reduced due to excessive use and polishing of the surfaces, especially the exterior surface. Some pendants, however, preserve a thickness up to 2.29 mm.

Ornaments in Phases 1–3 are found in a completed stage of manufacture and have signs of heavy usage. We hypothesize that this indicates that these ornaments were manufactured elsewhere. Manufacturing stages generally include blank preparation (cutting), perforating/drilling, trimming, and grinding (see Orton, 2008; Werner and Miller, 2018). During Phase 4, however, the assemblages contain broken pieces or blanks, and non-completed preforms with drilling holes on one or both sides: these can be identified as by-products, abandoned pieces, and other indicators of manufacture on site. This could mean a shift to local production, where Shizitan inhabitants may have carried out all stages of the process, from collecting OES, transporting OES fragments and blanks with them (or storing them at what would become a site favored for OES ornament production), and manufacturing the ornament products locally when and where they were needed. It is only from Phase 4, around 12 Ka cal BP, that we have these indicators of localized ornament-making, and this raises new questions about other changes that might be occurring in site occupation and activities at Shizitan 9 during the YD.

From where the OES raw material originated—local or distant—is another important but still unanswerable question. Although it is difficult to know how the hunter–gatherers of Shizitan acquired OES, because of the presence of blanks in Phase 4, for this stage, it can be hypothesized that they collected broken OES pieces within the range of their mobility (Song and Shi, 2013a; Song and Shi, 2013b). In Phases 1–3, no evidence of Shizitan area production has been found nor is there evidence anywhere else in the wider region: there are only finished ornaments, so we hypothesize that they could have been manufactured elsewhere. OES raw material apparently was not abundant in the Shizitan region as no pieces of OES are ever found in non-cultural sediments nor were found over 10 years of field investigations across the region. Their scarcity and perhaps more distant sourcing is also hinted at by the lack of evidence at the sites of ostrich eggs serving as a food resource since observation of the interior OES surfaces indicates that the eggshell present at the sites had been incubated and hatched. This would mean OES is present at sites only because finished ornaments were brought to the site or because limited numbers of pieces of OES were brought to the site to be made into ornaments.

Standardization and Size Reduction of Ornaments With the Improvement of Drilling Technology

The OES productions at Shizitan can be classified into pendants and beads according to how the ornaments would have been strung or suspended, or, in other terms, how they would have been displayed. As mentioned above, pendants are those ornaments individually suspended from a knot at what becomes the top orientation of the ornament (Song and Shi, 2013a). Such pendants could have been worn on the body or attached to garments or other items. The mode of stringing and suspension for pendants emphasizes the display of their broader surfaces (front or back, or what was the exterior or interior surface of the OES), and these pendants typically have a glossy surface for such display purposes. Furthermore, the BW/AD ratio, discussed above, is much larger for pendants (=1.57), reflecting the objective of producing a larger display of the shell surface. Bead production had different objectives that emphasize uniformity and the rhythm of beads strung together with each other, rather than a larger relative display surface of an individual bead.

The diachronic view afforded by the Shizitan localities shows that pendants and beads are not just typologically (formally) distinct but are manufactured and favored in distinct time periods through relatively independent systems of production with different objectives related to differing purposes of the ornaments' display.

Pendants appear first, when core and flake assemblages still comprise the lithic technological record at Shizitan. Although there is a gap in the record after 24 Ka cal BP for pendants (which is also after microblades appear), they are last present just after ca. 20 Ka cal BP. Beads first appear, in a completed form, in the Shizitan record during the LGM, contemporaneous with the appearance of the early microblade industry in SZT29 Layer 7 Spits 2–1, and then, beads persist and prevail in the record from 24 Ka cal BP onward through the Terminal Pleistocene. However, evidence for possible local production at Shizitan appears only in Phase 4, correlating with the Younger Dryas, in Shizitan 9 Level 4. The beads from this level are remarkably smaller in size (average diameter = 4.05) than earlier beads. This may be due to changing styles and tastes, to changing modes of stringing or affixing beads, and/or possibly to greater scarcity of the OES raw material during the YD. The fact that this change occurs within the context of the climatic and environmental downturn of the YD, along with potential changes in animal (Song et al., 2017; Zhang et al., 2019) and plant (Liu et al., 2011) exploitation patterns, as well as what our preliminary research indicates might be technical changes in microblade production at Shizitan 9, should also be considered.

Technical changes in the manufacturing process of the OES ornaments can also be observed, as has been studied for the drilling processes for OES at Shuidonggou (Yang et al., 2016; Wei et al., 2017) and for mollusk shell ornaments from SZT9, 12A, and 29 (Song et al., 2011). Two interrelated trends are noted that had to be accompanied by technological developments in drilling: these result in the gradual increase in BW/AD accompanied by, or resultant from, the decreasing bead aperture diameter (even as the bead diameter itself was greatly decreased in Phase 4). The earliest beads at Shuidonggou and Shizitan were likely made with flake-tool drillers as microblade technology was not yet available. The later production of smaller bead holes benefited from better drilling tools, which likely used drill bits made of microblades (Song et al., 2011). Although dating to the Early Holocene, slightly later than SZT9, this has also been shown by microscopic analysis, usewear, and experimental studies at Shuidonggou Locality 12 (Yang et al., 2016). The objective of drilling holes of smaller diameter would relate to changes in the modes of stringing and in the desired type of suspension of the ornaments. Smaller holes can imply the use of thinner strands and thus perhaps changes in techniques for producing string from the plant fiber (e.g., see Hardy, 2008) or changes in the preparation and use of animal fibers, such as sinew, hair, or wool. We hypothesize that the smaller hole (and the more standardized bead size) was directed toward concerns for stringing beads together to give a uniform appearance and for them to be more steadily threaded on the string, which would have been close in thickness to the beads' AD. This objective was met by the observed greater standardization in the production of the ornament size and shape, improvements in the drilling technology to produce smaller holes, and perhaps by (unobserved) improvements in producing appropriate fibers for stringing.

The clear reduction in size of OES ornaments is the most noteworthy change through time, and this needs to be considered further. The average diameter of Phase 4 beads (4.05 mm) are 27% smaller than the next smallest beads, from Shizitan 12G in Phase 3. Although we cannot determine the reasons for the decreasing size, in addition to the changing environment, economy, and technology mentioned above, potential changes in site functions and hunter–gatherer social organization and social networks would correlate with the changes in the bead size as well. For Shuidonggou 2, Wei et al. (2017) note that because smaller OES beads require greater investment of time and effort to manufacture and more specialized skills, and because their processing involves greater risk of failure than larger ornaments, in embodying these differences, the meanings that smaller beads may signal could be different; they also cite ethnographic examples of African groups in market economies reserving smaller beads for themselves while selling larger beads. We note an archaeological example, from southern Africa, of changes in OES bead size that accompanied changes in regional economies and competition between herder and hunter–gatherer groups. After herding arrived in the region at 2000 BP, OES beads at subsequent herder sites were always larger than those associated with forager sites, even though regional differences in bead size were subtle, on the order of millimeters (Jacobson, 1987a; Jacobson, 1987b; Smith et al., 1991; Sadr et al., 2003; Wilmsen, 2015; Miller and Sawchuk, 2019). The trends at Shizitan deserve further investigation into their relationships with changes in economy, social organization, cultural communication, and ideology, or even the movements of new populations into the region. While OES ornament size reduces by the time period at Shizitan, at Shuidonggou at ca. 30,000 years ago, Wei et al. (2017) argue that the differing bead sizes and types are found within a narrow-enough time range that the differences in beads in the cultural layer are resultant from the presence of different human groups with unique types of beads at the site.

Changes in OES Ornament Color Modification

As shown in **Figure 3**, the pendants in Phase 1 were all black or gray in color. Such coloration can be a result of heat treatment (intentional) or burning (unintentional) but possibly could result from post-depositional taphonomic processes that have not been identified. Heat treatment of the ornament material is an intentional activity by the ornament makers done to enhance the visual impact of the ornament or to allow the ornament to convey meaning through the special colors produced, and to alter the material's physical properties for workability (e.g., Godfrey-Smith and Ilani, 2004; d'Errico et al., 2010; Salomon et al., 2012).

FIGURE 8 | OES boiling experiment. The image shows a piece of OES that had been partially suspended in boiling water. The color change of the submerged part (top), followed by the color transition at the water line, can be seen.

This is supported by examples in modern bead-working (Schoeman, 1983; Wickler and Seibt, 1995). The natural color of the OES is light yellow to white, but the coloration of archaeological OES ornaments, such as some at Shizitan, can be altered. It can be difficult to ascertain if such color modification of the OES was intentional or not. Perhaps natural coloration was not preferred by the earlier Shizitan bead makers (but was by the later ones), and so they intentionally burned the OES to turn it black or gray. However, unintentional burning or post-manufacturing taphonomic processes could have altered the color of the OES. OES heating experiments by Craig et al. (2020) demonstrate that while furnace heating to 200, 350, 550, and 700°C can produce colors found archaeologically, physical changes in the OES from 350°C make the material subject to easier breakage during working. Colors produced by Craig et al. (2020), Collins and Steele (2017), and Texier et al. (2013) in the 200–350°C range include hues of yellow, orange, reds, and brown, but grays appear only above 350°C, and typically in the higher temperature ranges that increase the breakability of the OES. This favors an explanation of the Phase 1 OES as having unintentional color modification.

While these experimental studies of OES color change have focused on fire as the heat source in an open-air environment, here we present one preliminary test to see if boiling would also alter color. One author (YHS) partially suspended a piece of OES in boiling water. One-time boiling resulted in multiple colors: the coloration near the water surface line transitions from yellow to red for the submerged part (**Figure 8**). Further controlled experimental studies of heat changes are planned.

We also note other evidence that needs to be considered in assessing intentionality of color modification. First, color change also can be found combined with bright polishing, which if intentional rather than from usewear, was performed to produce beautifying surface effects. One OES bead at Shuidonggou 2 (SDG2: 6500) had been heat-treated after manufacture to turn it black but has usewear from after the bead had been treated (Wei et al., 2017). Second, there are also parallel examples of heating of other materials. Marine mollusk shell pendants with a drilled hole in the top were also burnt to a black color (Song and Shi, 2013b: Figure 13), but these could have been subjected to the same processes, intentional or unintentional/post-manufacturing, as the OES pendants. One line of evidence, however, allows us to argue for some forms of intentional heat treatment being present from the time period of Layer 7 Spits 2–1. Microblades appear in these spits, and preliminary studies indicate that Shizitan 29 knappers employed heat treatment on the flint they used as a necessary step in the production process that facilitates the removal of the microblades by the pressure technique (Song et al., 2019). They, thus, had knowledge of the potential for heat to alter the physical qualities of materials for technical advantage. We should still ask, then, if in the same way, ornament makers were able to control OES color modification.

Modification of OES color through heating, burning, or post-depositional processes is not seen after SZT29 Layer 7 Spits 5–2, with one exception, a burnt OES piece with a half-completed hole drilled from one surface found in SZT 9 Layer 4: this piece was abandoned after drilling failure and was discarded into a hearth with other animal bones, so its color modification was unintentional.

It is noteworthy that all of the ornaments in Shizitan Layer 7 Spits 5–2 were burnt, but we found no hearths in these spits. In layers where hearths are found, to the contrary, all of the OES ornaments around the hearths still maintained their natural, ivory color, showing no signs of color modification through heating (with the one exception from SZT 9).

Ochre

Although heat treatment may not have been applied for color modification, coloration of ornaments was still carried out at Shizitan using red ochre, which is found in SZT29 Layer 7 Spits 2–1 and onward. Excavated examples include two ochre pieces with ground facets, one from Layer 7 Spits 1–2 (**Figure 9**: 2) and the other from SZT9 Layer 4 (**Figure 9**: 1). Clear parallel striations from grinding are observed on 2–3 ground facets of each piece of the ore. Also, traces of the ochre on grinding slabs (**Figure 9**: 3, 5) and handstones (**Figure 9**: 4) show that humans may have smashed the ochre to grind the smaller pieces into pigment powder. Such pigments are observed on the surfaces of the naturally colored OES (e.g., on the inner surface of a bead from SZT29 Layer 2) (**Figure 9**: 6), and they have remained attached even after usage (apparent usewear) and post-depositional processes. No such pigments are observed on the black/gray pendants from SZT29 Layer 7 Spits 5–2 nor were ochre pieces found associated in these deposits.

A grinding slab from Shizitan 9 Layer 4 had microscopic residues of hematite ochre in addition to evidence for processing a broad range wild plant foods (Liu et al., 2011), and the slab was associated with ochre ore fragments, two of which had striations (Shizitan Archaeological Team, 2010). A second grinding slab from the same level had similar usewear patterns to abrading mollusk shell and stone (Liu et al., 2011), leading us to conjecture their usage during processing of OES ornaments, as observed on

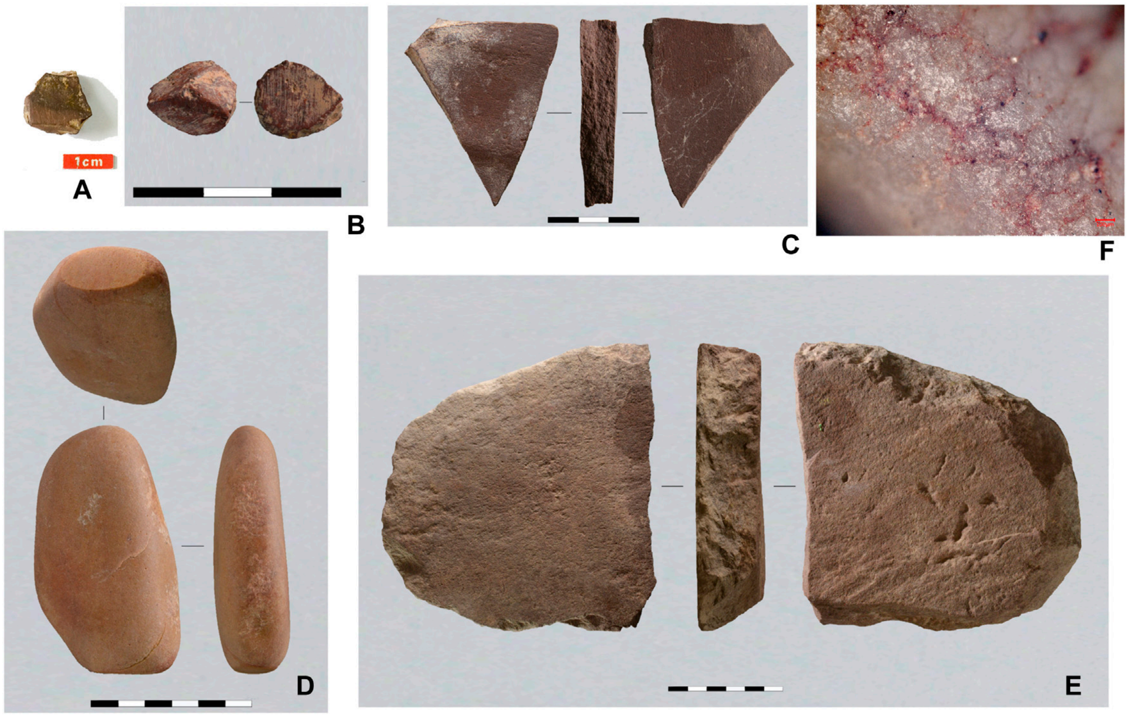

FIGURE 9 | (A). Ochre (S9:370) from SZT9 Layer 4; **(B)**. Ochre (S29:60–103) from SZT29 Layer 7 Spits 2–1; **(C, E)**. Grinding slabs (S29:66–109 and S29:13110) from SZT29 Layer 7 Spits 2–1 with traces of ochre; **(D)**. Handstone (S29:11,959) from SZT29 Layer 7 Spits 2–1; **(F)**. Ochre pigment on the inner surface of a bead from SZT29 Layer 2.

Shuidonggou beads (Wei et al., 2017). These slabs and the coloring of OES beads with hematite ochre during Phase 4 indicate another aspect of the complete production process carried out on site in this stage and is another significant aspect of bead production and usage at Shizitan during the YD. The question should be raised if this relates to new forms of social signaling being required during this time period of likely increased stress and social competition. However, as mentioned above, ochre compounds on OES ornaments are found 19,000 years earlier at Shuidonggou 2 (Pitarch Marti et al., 2017), perhaps significantly at a time when "indigenous" advanced core and flake industries are replacing an "intrusive" blade industry (see Li et al., 2019).

CONCLUSION

Ostrich eggshell ornaments are infrequent discoveries in Late Paleolithic sites in North China. While their archaeological rarity may reflect their fragility and difficulty to be preserved and recovered, it is also a true reflection of the low amounts available in the Paleolithic period. When combined with their aesthetic qualities, their rarity also produces their value over other materials in serving in symbolic and social signaling roles that we only understand abstractly. The 41 OES items recovered at the Shizitan site localities, with well-dated stratigraphic proveniences and rich, associated material culture, provide us a rare opportunity to understand the diachronic changes in the non-edible utilization of this animal resource over time, particularly technological and typological developments that reflect changing human objectives in manufacturing and usage (as ornaments). These changes may relate to changes in hunter–gatherer lifestyle and activities at sites through the major climatic and environmental changes from 28–11 Ka cal BP, including the LGM, amelioration, and the YD. We divide OES ornament usage into four distinct phases during this time range and are able to note a number of significant changes through these phases, including the change from importing finished ornaments to local manufacture; typological changes from pendants to beads; changes in size preferences from ornaments, to larger-sized beads, to small beads; changes in the drilling technology, such as from flake-driller to microblade-driller; and changing preferences in color modification, including heating/burning and coloring using red ochre pigments. These all provide insights into potential roles that OES ornaments may have played and changing meanings of these objects among the Shizitan hunter–gatherer groups in different time periods.

OES ornaments, thus, provide another pathway to understanding the expression of behavioral modernity and an "Upper Paleolithic Revolution" in Late Paleolithic North China (Bar-Yosef, 2002; Bar-Yosef, 2007; Norton and Jin, 2009). They reflect visual signaling on a small scale (beadwork or pendants) using a rare animal resource (ostrich eggs). We also note that this usage of OES excludes the egg's potential role in nutrition and may be an indicator of the low availability of the ostrich shell within the usual range of mobility of Shizitan's inhabitants: as with the marine mollusk shell at the site, OES may represent broader social networks and exchange. Further comparison on a larger scale of objects and materials such as OES and marine shell is worth carrying out to shed further light on the nature of communication amongst hunter–gatherer groups in North China through the Last Glacial period, and this should also have repercussions for reconstructing broader patterns of mobility and migration of modern human populations across northeastern Asia and into the Americas.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

JS directed the excavations of the localities of the Shizitan site. Project administration was carried out by YS and JS. Funding acquisition was carried out by YS and DC. Conceptualization was performed by YS and JS. Laboratory analyses of the ornaments and experimental studies were conducted by YS. Methodology was performed by YS and JS. Formal analysis was carried out by YS and JS. Visualization and investigation was performed by YS, JS, and DC. Original draft was written by YS and DC. Review and editing was performed by DC and YS.

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Farmers or Nomads: Isotopic Evidence of Human–Animal Interactions (770BCE to 221BCE) in Northern Shaanxi, China

Cui Mengjie[1,2], Shang Xue[2]*, Hu Yaowu[3]*, Ding Yan[4], Li Yanfeng[4] and Hu Songmei[4]

[1]Key Laboratory of Vertebrate Evolution and Human Origins of Chinese Academy of Sciences, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, China, [2]Department of Archaeology and Anthropology, University of Chinese Academy of Sciences, Beijing, China, [3]Department of Cultural Heritage and Museology, Fudan University, Shanghai, China, [4]Shaanxi Academy of Archaeology, Xi'an, China

Chinese history is composed of the contest, war, and admixture between the nomads in the north plateau and the farmers in central China. During the Eastern Zhou Period (770–221 BCE), nomadic groups, such as Rong (戎) and Di (狄), occupied the Eurasian Steppes and had frequent contact with the farmer group in Central China according historic records. This created a geographic boundary between the two groups named the agro-pastoral interweaving belt. To explore the impact of ethnic integration and human–animal interaction during the Eastern Zhou Dynasty, carbon and nitrogen stable isotope analysis of humans and animals at the Chongpingyuan site, Shaanxi, was undertaken. The $\delta^{13}C$ (mean: -7.9 ± 0.5‰, n = 17) and $\delta^{15}N$ values (mean: 8.8 ± 0.6‰, n = 17) for human and pigs (mean $\delta^{13}C$: –8.1 ± 0.5‰; mean $\delta^{15}N$:7.5 ± 0.5‰, n = 2) revealed that they consumed C_4-based foods mainly while the $\delta^{13}C$ and $\delta^{15}N$ values of cattle (–17.6‰, 4.3‰, n = 1), horse (–17.1‰, 4.1‰, n = 1), and sheep (mean: –17.4 ± 1.5‰, 6.0 ± 0.8‰, n = 7) suggest that they relied on C_3 plants supplemented with minor C_4 plants. Based on the archaeological and historic contexts, we infer that humans at Chongpingyuan survived on an agro-pastoral economy with millet agriculture as the economic foundation. Given the isotopic spacing between humans and animals, we found that pigs contributed to the main sources of animal protein, whereas other animals might have been provisioned for other purposes, such as rituals or properties. In general, no significantly dietary differences between genders and funeral customs are found, but people with abundant burial objects seem to have consumed more animal protein, possibly related to social heterogeneity.

Keywords: Eastern Zhou Dynasty, Northern Shaanxi, agro-pastoral economics, subsistence strategy, stable isotope analysis, human-animal interaction

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Manuel Domínguez-Rodrigo, University of Alcalá, Spain

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Petra Vaiglova, Washington University in St. Louis, United States
Weichao Wu, Stockholm University, Sweden

****Correspondence:***
Shang Xue
shangxue@ucas.ac.cn
Hu Yaowu
ywhu@fudan.edu.cn

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INTRODUCTION

Influenced by the fluctuation of East Asia monsoon and human activities, there was an agro-pastoral ecotone in Northern China (Chen et al., 2010; Shi and Shi, 2018; Damette et al., 2020). Northern Shaanxi is located on the Loess Plateau, a typical area of agro-pastoral ecotone in history (Shi, 1999). Historic records suggest several ethnic groups, such as Rong (戎), Di (狄), and Huaxia (華夏),

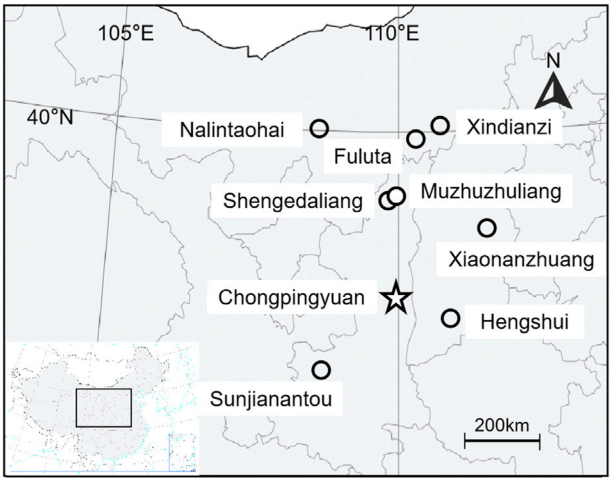

FIGURE 1 | Locations of the study area and archaeological sites mentioned.

FIGURE 2 | Geography of the Chongpingyuan site.

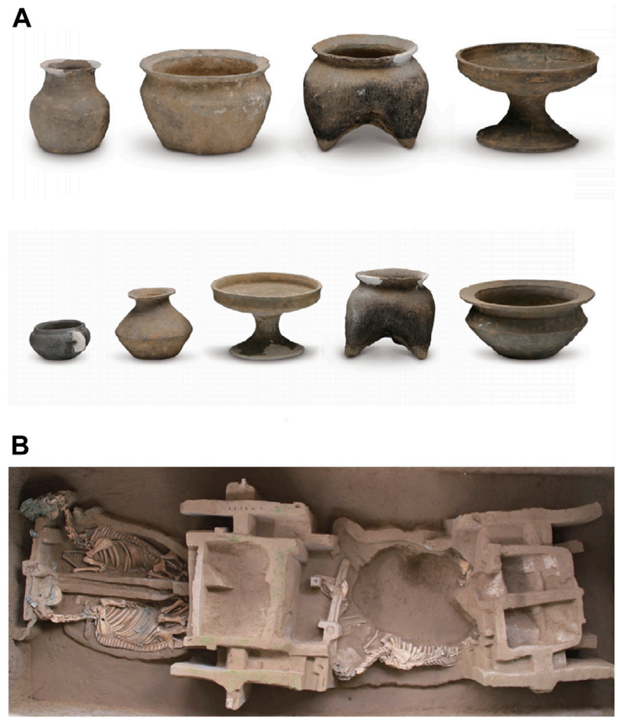

FIGURE 3 | Pottery **(A)** and chariot-and-horse pit **(B)** recovered from the tombs of the Chongpingyuan site (Ding et al., 2018).

occupied here since the Western Zhou Dynasty (1046BCE to 771BCE) (Yang, 2009; Shan, 2015). In the East Zhou period, archaeological remains affiliated to Eurasian steppe and Central Plains styles could be found (Teng and Wang, 2011; Shan, 2015), indicating the coexistence of multiple cultures and populations living simultaneously in this region. So far, there is a lack of direct evidence of human subsistence strategies and human–animal interactions in this region to show the cultural and population interplay between different ethnic groups.

The Chongpingyuan site (N36°01, E110°07) is located in Yichuan County of Yan'an City, Shaanxi Province of China (Ding et al., 2018). The site is on the central part of Loess Plateau, with ravines crisscrossing the territory (**Figures 1**, **2**). In 2014, the Shaanxi Provincial Institute of Archaeology and Yichuan County Museum conducted exploration and excavation of the Chongpingyuan site. Within the site, 21 tombs, one chariot-and-horse pit, three ash pits, and two ditches were unearthed (Ding et al., 2018). The characteristics of the funeral objects and chariot-and-horse pit (**Figure 3**) in the Chongpingyuan site were similar to the Central Plains (Li, 2018), but the tomb orientations and the customs of animal sacrifices in some tombs suggested that local ethnic culture might also have had an impact on the Chongpingyuan site (Chen, 2020; Sun, 2020).

By analyzing the carbon and nitrogen stable isotopes in the bone collagen of human and animals, we can understand the contribution of C_4- or C_3-based foods in human diets (Ambrose, 1991; Hedges, 2003; Lee-Thorp, 2008) and the categories of animal protein (Kohl et al., 1980). Isotope analysis has succeeded in revealing prehistoric human subsistence strategies under different natural environments and cultural backgrounds in this region (Zhang et al., 2006; Zhang et al., 2017; Tang et al., 2018; Liu et al., 2021). In this study, stable isotope analysis of humans and animals at the Chongpingyuan site in northern Shaanxi was undertaken to investigate the human lifestyles and interactions with humans and animals during the Eastern Zhou Dynasty.

MATERIALS AND METHODS

Sample Selection

In this study, 42 samples in total from 17 humans (including 15 ribs and 16 long bones), seven sheep, two pigs, one cow, and one horse were used (**Table 1**). In particular, the human samples were selected according to the differences of gender, burial posture, and sacrificed animals (**Table 2**). The identification of age, gender, and other physical characteristics was performed by

TABLE 1 | The δ13C and δ15N values from the Chongpingyuan site.

Lab No.	Context	Species	Skeletal elements	%C	%N	Atomic C/N	δ^{13}C (‰)	δ^{15}N (‰)
CP1	M44	Sheep	Limbs	44.2	15.2	3.4	−14.7	7.6
CP2	M48	Pig	Phalange	44.9	15.1	3.5	−7.6	7.1
CP3	M17	Cattle	Phalange	43.4	15.0	3.4	−17.6	4.3
CP4	M17	Sheep	Phalange	44.0	15.2	3.4	−18.0	6.2
CP5	M42	Sheep	Phalange	44.5	15.4	3.4	−16.2	6.0
CP6	M8	Sheep	Limb	43.5	15.2	3.3	−17.0	5.8
CP7	M8	Pig	Phalange	43.4	15.2	3.3	−8.5	8.0
CP8	M35	Sheep	Phalange	37.9	13.2	3.4	−19.6	5.1
CP9	M36	Sheep	Phalange	44.2	15.2	3.4	−17.8	5.6
CP10	M39	Sheep	Phalange	42.6	14.7	3.4	−18.5	5.5
CP11	K1	Horse	Limb	43.4	15.1	3.3	−17.1	4.1
CL8	M08	Human	Rib	45.4	16.8	3.2	−7.6	10.4
CL11	M11	Human	Rib	44.4	16.2	3.2	−8.1	10.2
CL29	M29	Human	Rib	46.1	16.9	3.2	−8.1	8.7
CL34	M34	Human	Rib	47.1	17.5	3.1	−8.4	8.5
CL36	M36	Human	Rib	45.4	16.5	3.2	−8.0	9.4
CL37	M37	Human	Rib	45.9	17.0	3.1	−7.5	8.8
CL38	M38	Human	Rib	46.6	16.9	3.2	−7.5	9.0
CL39	M39	Human	Rib	45.4	16.3	3.2	−7.6	9.0
CL40	M40	Human	Rib	43.8	15.9	3.2	−7.5	8.8
CL42	M42	Human	Rib	42.3	15.3	3.2	−7.6	9.0
CL43	M43	Human	Rib	47.7	17.6	3.2	−7.9	9.6
CL44	M44	Human	Rib	43.6	15.9	3.2	−8.0	10.4
CL46	M46	Human	Rib	47.0	17.6	3.1	−7.3	9.2
CL47	M47	Human	Rib	43.4	16.0	3.2	−7.9	8.2
CL48	M48	Human	Rib	43.7	15.7	3.2	−8.0	8.8
CR8	M08	Human	Femur	38.7	14.1	3.2	−7.6	10.4
CR11	M11	Human	Femur	47.0	17.4	3.2	−7.8	9.9
CR29	M29	Human	Humerus	45.8	16.8	3.2	−8.6	8.2
CR34	M34	Human	Humerus	46.2	16.9	3.2	−9.1	7.9
CR35	M35	Human	Femur	47.2	17.3	3.2	−8.5	8.8
CR36	M36	Human	Femur	45.1	16.5	3.2	−8.3	9.0
CR37	M37	Human	Femur	47.6	17.4	3.2	−7.5	8.9
CR38	M38	Human	Femur	44.4	16.4	3.2	−7.2	8.6
CR39	M39	Human	Femur	41.9	15.3	3.2	−7.5	9.1
CR40	M40	Human	Radius	45.1	16.5	3.2	−7.8	8.8
CR41	M41	Human	Femur	47.0	17.3	3.2	−7.6	8.3
CR42	M42	Human	Femur	45.0	16.6	3.2	−8.0	8.5
CR44	M44	Human	Femur	43.4	15.8	3.2	−8.0	9.5
CR46	M46	Human	Femur	44.9	16.6	3.2	−8.1	8.3
CR47	M47	Human	Radius	41.6	15.4	3.1	−7.7	8.0
CR48	M48	Human	Femur	46.5	17.1	3.2	−7.7	8.6

Chen (Chen et al., 2018). Meanwhile, other archaeological contexts come from the excavation briefs (Ding et al., 2018).

Radiocarbon Dating of Collagen

Two human bone samples were AMS Radiocarbon dated by Beta Analytic, Inc., and were calibrated by the BetaCal4.20: HPD method (INTCAL20). The results show that the age of M8 is 2480 ± 30 cal a BP, and the age of M34 is 2410 ± 30 cal a BP (**Table 3**). It showed that these people lived in the spring and autumn period (770 to 403BCE), and the result is consistent with the judgment given through the archaeological remains (Chen et al., 2018; Ding et al., 2018).

Collagen Preparation and Isotopic Measurements

The method for extracting collagen came from Richards and Hedges (Richards and Hedges, 1999) and was modified with ultrafiltration before lyophilization (Brown et al., 2016). After cleaning the contaminants on the surface of bones, 2–3 g of bone samples were weighed and immersed in 0.5 M HCl at 4°C. HCl was replaced every 48 h until there were no obvious bubbles on the surface of the bones, and then the samples were eluted to neutral with deionized water. The neutral samples were soaked in 0.125 M NaOH for 20 h at 4°C and then washed with deionized water until neutral. The bone samples were soaked in 0.001M HCl, heated in an oven at 70°C for 48 h, and then filtered while hot to obtain a collagen solution. Finally, the solution was freeze-dried to obtain collagen.

The stable isotope values of C and N contents of the collagen samples were measured by the laboratory of the Department of Archaeology and Anthropology, University of Chinese Academy of Sciences. The samples were measured on an IsoPrime-100 IRMS. The contents of carbon and nitrogen elements were determined with sulfanilamide as the standard substance.

TABLE 2 | The burial details of Chongpingyuan tombs (Chen et al., 2018; Ding et al., 2018).

Context	Gender	Age	Burial posture	Sacrifice	Animals
M08	Male	45–50	Straight limbs	Yes	Sheep, pig
M11	Female	30–35	Straight limbs	No	None
M29	Female	37–45	Straight limbs	No	None
M34	Female	29–30	Bent limbs	No	None
M35	Female	31–34	Straight limbs	Yes	Sheep
M36	Female	60	Bent limbs	Yes	Sheep
M37	Female	45–50	Bent limbs	No	None
M38	Male	20–25	Bent limbs	No	None
M39	Male	60	Straight limbs	Yes	Sheep
M40	Male	60	Straight limbs	No	None
M41	Female	20–45	Straight limbs	No	None
M42	Female	20–22	Bent limbs	Yes	Sheep
M43	Female	Unknown	Straight limbs	Yes	Sheep
M44	Male	28–30	Bent limbs	Yes	Sheep
M46	Male	45–50	Straight limbs	No	None
M47	Female	40–50	Bent limbs	No	None
M48	Female	20–22	Bent limbs	Yes	Pig

Stable isotope of carbon was calibrated to VPDB and AIR standards by using IAEA-600, IAEA-CH-6, IAEA-N-2, USG5 40 and USG5 41 as standard substance. Two-point calibration was used to calibrate the raw isotope values. After every 10 samples, a standard collagen sample made by the laboratory (δ^{13}C −14.7 ± 0.2‰, δ^{15}N 7.0 ± 0.2‰) was inserted to the sample list to calibrate the precision. The precision for C and N was determined to±0.2‰ of calibration standards, check standards.

All 42 collagen samples were successfully extracted (**Table 1**). The %C values (37.9%–47.7%, average 44.6% ± 2.1%) were higher than 13%, and the %N values (13.2%–17.6%, average 16.1% ± 1.0%) were higher than 4.8% (Deniro, 1985). The atomic C/N ratios of bone collagen were between 3.1 and 3.4 within the acceptable range of 2.9–3.6 (Ambrose, 1990). It reflected that samples of collagen were not degraded, and they were useable for stable isotope analysis.

RESULT AND DISCUSSION

Animal Feeding Practices

The stable isotope value of an organism (human and animals) depends on the isotopic composition of its food. The δ^{13}C value of C_3 plants is in the range of -30–23‰ (average −26.5‰), and δ^{13}C value of C_4 plants range of −16–9‰ (average −12.5‰) (Farquhar et al., 1989; van der Merwe and Medina, 1991). From food to collagen, the δ^{13}C value is enriched 5‰, and this value was varied because of the different composition of micro-biomolecules (Lee-Thorp et al., 1989; Lee-Thorp, 2008) while the δ^{15}N value enriched 3-5‰(Hedges and Reynard, 2007).

The δ^{13}C and δ^{15}N values of sheep, pigs, cattle, and horses are all shown on **Table 1** and **Figure 4**. The ranges of stable isotope values vary greatly from one species to another, indicating that animals may be raised in different ways. The pigs have the most positive δ^{13}C values (mean: −8.1 ± 0.5‰, n = 2) and the highest δ^{15}N values (7.5 ± 0.5‰, n = 2), which indicates that pigs consumed C_4 based foods, C_4 plants and/or animals consuming C_4 plants mainly (Hu, 2019; Hu et al., 2020; Hou et al., 2021a; Hou et al., 2021b). Considering the fact that there is a long history of millet agriculture in northern Shaanxi (Sheng et al., 2018) and both millets (*Panicum miliaceum, Setaria italica*) are attributed to C_4 plants crops while the local vegetation was dominated by C_3 plants (Zhou et al., 2009), we suggest that pigs might have been fed by millet by-products.

Sheep had the largest numbers in all unearthed domestic animals (n = 7) and had varied isotopic data. Their mean value δ^{13}C −17.4 ± 1.5‰ (range −19.6–14.7‰) suggests that sheep survived on mixed C_3/C_4-based diets and consumed C_4 food to varying degrees. The lowest δ^{13}C value of sheep (−19.6‰) reflected a C_3-based diet, and it was close to wild animals in northern Shaanxi (Wang et al., 2018). Meanwhile, the highest δ^{13}C value (−14.7‰) suggested a higher proportion of C_4 plants in its food. The large range of δ^{13}C value suggested that sheep probably had a wide range of foraging ecology. δ^{13}C value of cattle (n = 1) was −17.6‰, and δ^{13}C value of horse (n = 1) was −17.1‰, indicating that both cattle and horse fed on mixed C_3/C_4 plants with C3 plants dominated. The similarity of δ^{13}C values among cattle, horse, and sheep suggests that they probably subsisted on similar fodders. Comparing the isotope results of sheep on Chongpingyuan site with sheep of different feeding patterns on modern Inner Mongolia, the isotope results of sheep on Chongpingyuan was between those of grassland pasturing sheep (δ^{13}C −21.6 ± 3.5‰, n = 87) and barn feeding sheep (δ^{13}C −14.6 ± 1.0‰, n = 17) (Wang, 2021) suggesting that sheep in Chongpingyuan were probably mixed grassland pasturing and barn feeding. C_3 plants are the main fodder for cattle, sheep, and horse, reflecting their diets based on wild plants in the natural environment mainly (Zhou et al., 2009). However, roles of C_4 foods could not be ignored. The diets of these domestic animals contained different proportions of C_4 plants like millet by-products. It showed that animal husbandry in Chongpingyuan was closely related to the millet agriculture. In response to winter grass shortages, herders supplemented their grazing animals with C_4 fodders, which would lead to higher δ^{13}C values (Makarewicz, 2015). The mixed C_3/C_4 diet suggested people in the Eastern

TABLE 3 | Radiocarbon dating of collagen.

Sample	Material	Conventional Age	Calendar Calibration
M8	bone collagen	2480 ± 30 BP	(95.4%) 772–478 cal BC (2721–2427 cal BP)
M34	bone collagen	2410 ± 30 BP	(81%) 550–399 cal BC (2499–2348 cal BP) (10%) 743–692 cal BC (2692–2641 cal BP) (4.5%) 665–647 cal BC (2614–2596 cal BP)

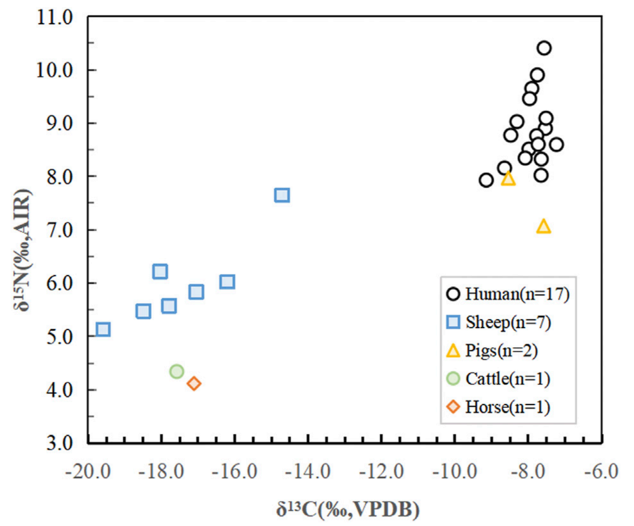

FIGURE 4 | Scatterplot of isotopic data from humans and animals at Chongpingyuan.

Zhou Dynasty probably had begun to use millet by products to help livestock survive in the winter.

The kill-off patterns of animals were closely related to their usages by humans. Most of the sacrificial animals in Chongpingyuan were juveniles, which suggested they might be raised as meat animals (Payne, 1973). Meanwhile, some sheep unearthed in Chongpingyuan were adult individuals that indicated they might be used for second products (Vigne and Helmer, 2007). Ancient people from the Taosi site in the Bronze Age may have started raising sheep for second products, such as wool, and these sheep would be slaughtered after adulthood (Brunson et al., 2016). People in the Eastern Zhou Dynasty might already have diverse patterns of livestock husbandry and utilization.

According to the *Liji* (禮記), people used livestock as sacrifice, and people chose different animals according to their status as cattle were the highest grade called *Tailao* (太牢), sheep the next called *Shaolao* (少牢), and pigs the lowest grade called *Kuishi* (馈食) (Xie, 2018). According to the archaeological discoveries although sheep were not mainly a meat source of human diets, they were the most common sacrificial animals throughout the Eastern Zhou Dynasty (Zuo, 2018; Zhao, 2020; Hou et al., 2021a). In that case, sacrificial animals of Chongpingyuan were the manifestation of this sacrificial culture.

The Human Diets

In **Table 1**, the $\delta^{13}C$ values of the individuals were in a very narrow range (−9.2–7.2‰) with the mean of −7.9 ± 0.5‰ (n = 17). It suggests that these individuals consumed C_4-based foods. Their high $\delta^{13}C$ values indicate that millet agriculture played a significant role in their foods. The mean $\delta^{15}N$ value of human (n = 17) is 8.8 ± 0.6‰, characteristic of terrestrial animal protein. However, the large range of $\delta^{15}N$ values, from 7.9 to 10.4‰, indicated meat intake might be internally different within the human group.

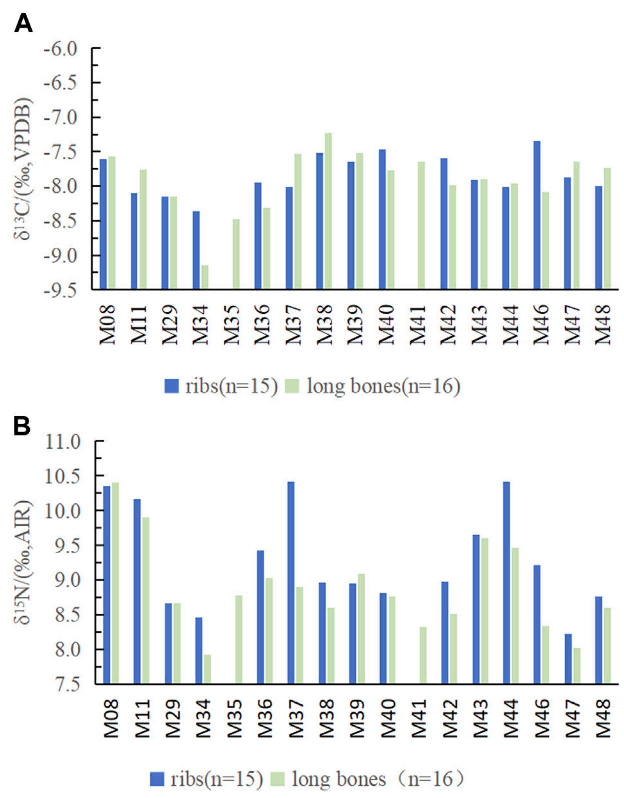

FIGURE 5 | Plots of $\delta^{13}C$ **(A)** and $\delta^{15}N$ **(B)** values of human ribs and long bones.

From the diet protein to collagen, the $\delta^{13}C$ values were enriched by 1–1.5‰, (Lee-Thorp, 2008) while $\delta^{15}N$ values enriched 3–5‰ (Hedges and Reynard, 2007). Comparison of $\delta^{13}C$ and $\delta^{15}N$ values among humans and animals indicates between pigs and humans (−0.2‰, 1.3‰), sheep and humans (9.5‰, 2.8‰), cattle and humans (9.8‰, 4.7‰), and horse and humans (9.3‰, 4.5‰). When the isotopic fractionation from the diets to collagen is considered, we can see that only pigs have the similar $\delta^{13}C$ and $\delta^{15}N$ values to humans, strongly indicating the animal protein in human diets came from pigs mainly but not from other animals. Other animals could be utilized for other purposes, such as animal power, wool, or milk (Zhao et al., 2017; Hou et al., 2021a).

Given the turnover differences of various skeletal elements, the stable isotope values of the ribs indicated their average diets for 2–5 years before death, whereas those of long bones indicated the average diet for 10–15 years before death (Parfitt, 2002; Hedges et al., 2007). Comparison of the $\delta^{13}C$ and $\delta^{15}N$ values from ribs and long bones in the same individual shows their diet changed throughout their different lifetime (**Figure 5**). The mean $\delta^{13}C$ value of ribs (n = 15) is −7.8 ± 0.3‰, and the value of long bones (n = 16) is −7.9 ± 0.4‰ (**Figure 5A**). The mean $\delta^{13}C$ difference between ribs and long bones (0.1‰) is within the analytical precision and paired t-test (p = 0.23, n = 14) indicates there is no significant difference, suggesting that their diets changed hardly. The mean $\delta^{15}N$ value of ribs (n = 15) is 9.3 ± 0.7‰, and the value of long bones (n = 16) is 8.8 ± 0.6‰ (**Figure 5B**). A paired t-test (p = .0004 < .01, n = 14) indicated there is significant increase (0.3 ± 0.3‰, n = 14) through time. This could be caused by the more animal protein consumption or abnormal physiology before death.

To test the possible internal differentiation in the Chongpingyuan people, isotope results were divided by gender (p_G), burial posture (p_P), and with or without sacrifices (p_S) in their tombs and used multivariate analysis of variance (MANOVA) to access the internal difference. The isotopic results reflected that the $\delta^{13}C$ values of the Chongpingyuan human group had no significant difference in these factors (p_G = 0.19, p_P = 0.82, p_S = 0.52). MANOVA of $\delta^{15}N$ values (p_G = 0.36, p_P = 0.31, p_S = 0.06) showed that gender and burial posture had no significant effect on meat consumption. However, the p value of whether to have sacrifices is close to 0.05, and the mean $\delta^{15}N$ values of humans with sacrifices (9.2 ± 0.6‰, n = 8) were higher than humans without sacrifices (8.6 ± 0.6‰, n = 9), suggesting sacrifice custom might be related to meat consumption.

However, some individuals have higher $\delta^{15}N$ values among the human population, like M08 (10.4‰), M11 (9.9‰), and M44 (9.5‰). The tomb of M08 was the second largest one in the Chongpingyuan site, and more funeral objects were found. Apart from M08, M44 also had many funeral objects. On the contrary, M34 had the lowest $\delta^{15}N$ value (7.9‰), indicating that she consumed the least animal protein. This could be related to her lower social status evidenced by the few items in her tomb (Ding et al., 2018). In ancient times, the rich owned more wealth, and they could consume better foods, which meant more animal protein in their food resources (Zhou, 2020). *Zhouli* (周禮) recorded that the Zhou Dynasty divided people into different classes and stipulated their daily life from various aspects, and the use of animals, including the consumption of diet meat and species of animals using for sacrifices (Chen, 2016). The social hierarchical structure affected the meat consumption of humans.

All in all, different genders and cultural characteristics did not have significant difference in the population's subsistence strategies, but the higher class seemed to consume more animal protein. All the people in the Chongpingyuan site lived on an agro-pastoral economy.

Agro-Pastoral Economy in Northern Shaanxi

After 4000 BP, the climate had deteriorated from warm and humid to dry and cold (Xu et al., 2020). In some areas in northern China, such as the Xinjiang and Hexi corridor, the proportion of agriculture in the livelihood economy decreased, and the stockbreeding component increased, eventually turning into a nomadic economy (Wang et al., 2019; Yang et al., 2019; Damette et al., 2020). Pollen evidence shows the decrease in trees and increase in herbs in northern Shaanxi after the Longshan Period (He et al., 2000).

The study of plant remains showed that people planted millet during the Neolithic Period in northern Shaanxi. Ancestors had already begun to grow millet in the Yangshao period, but the number and probability of archaeological excavations were very low (Sheng et al., 2017; Liu et al., 2019). Until the Longshan Period, agriculture in northern Shaanxi was developed as the number of food crops and the probability of excavation in the archaeological sites were significantly improved (Gao, 2017; Sheng et al., 2018; Liu et al., 2019). Although sheep and other pastoral-related animals began to appear in northern Shaanxi since 4500 a BP(Hu et al., 2016; Guo, 2017), isotopic evidence showed that the subsistence strategies were dominated by millet farming, and the grassland animal husbandry took very little part in the local economy (Chen et al., 2015; Chen et al., 2017). However, by the Eastern Zhou Dynasty, the amount of millet unearthed in archaeological sites was very small, and the probability of being unearthed was also very low (Liu et al., 2019), which implied that agriculture in this region probably encountered difficulties.

The comparison of isotopes of the people in the Longshan Period and the Eastern Zhou Period was similar to each other, which indicated that their diet structure stayed consistent over time (**Figure 6**). People in northern Shaanxi always lived on agro-pastoral economics from the late Longshan Period to the Eastern Zhou Period. Although there were negative factors to the agriculture, the local people did not show an obvious trend of nomadism. The complementary mixed economies of agriculture and livestock helped them challenge environmental degradation.

Subsistence Strategy Around Agro-Pastoral Ecotone

To better understand the subsistence strategies of local ancestors during the Eastern Zhou Dynasty, stable isotopes from the Chongpingyuan site were compared with data from surrounding archaeological sites, ranging from the West Zhou Period to the Qin and Han Dynasties. The locations of these sites are indicated in **Figure 1**, and their isotope data are indicated in **Table 4** and **Figure 7**.

The results show that, around the northern Shaanxi region, people from all those sites relied on C_4 food as their main food source. Among all these people, the people on the Chongpingyuan site had the highest $\delta^{13}C$ value, indicating that the people on the Chongpingyuan site also had the highest proportion of C_4 food in their food source. In other words, their food mainly depended on millet agriculture.

The Sunjiannantou, Xindianzi, and Nalintouhai people had relatively lower $\delta^{13}C$ values, which indicates that they also consumed a certain amount of C_3 food (Zhang et al., 2006; Ling et al., 2010; Zhang et al., 2012). The Xindianzi people, likely related to Huns (匈奴), had a more developed animal husbandry economy, and the C_3 food would come from the animals they graze in the wild (Zhang et al., 2006). Wheat was first introduced into China from Xinjiang 5700 a BP, and people in the central Plains began to grow a certain amount of wheat (Ling et al., 2010; Tang et al., 2018; Zhou et al., 2020). The lower isotope carbon value in some areas might be related to the promotion of wheat cultivation (Zhang et al., 2012; Tao et al., 2020). But people in most regions like the Chongpingyuan still relied on C_4 plants, millet, as their farming economics.

By comparing the $\delta^{15}N$ values of various sites, the data showed that the $\delta^{15}N$ values of the people in the Chongpingyuan site were

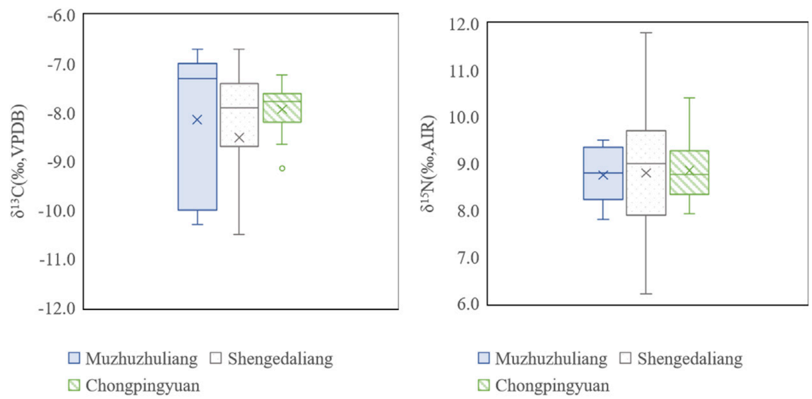

FIGURE 6 | The boxplots of carbon **(A)** and nitrogen isotopes **(B)** humans in Northern Shaanxi from the Longshan Period to the East Zhou Dynasty.

TABLE 4 | Summary of human collagen isotope results around Northern Shaanxi.

Site	Period	*n*	$\delta^{13}C \pm SD$ (‰)	$\delta^{15}N \pm SD$ (‰)	References
Shengedaliang	1875 to 1665 BCE	28	−8.5 ± 1.8	8.8 ± 1.4	Chen et al. (2017)
Muzhuzhuliang	1950 to 1780 BCE	7	−8.2 ± 1.5	8.8 ± 0.6	Chen et al. (2015)
Hengshui	1046 to 680 BCE	82	−8.3 ± 1.2	9.0 ± 1.0	Sun (2019)
Sunjianantou	770 to 221 BCE	25	−10.8 ± 1.5	8.5 ± 0.6	Ling et al. (2010)
Chongpingyuan	770 to 403 BCE	17	−7.9 ± 0.5	8.8 ± 0.6	This study
Xindianzi	476 to 453 BCE	20	−11.5 ± 0.9	10.3 ± 0.8	Zhang et al. (2006)
Xiaonanzhuang	550 to 403 BCE	16	−8.0 ± 0.4	10.5 ± 0.9	Tang et al. (2018)
Fuluta	221 BCE to 8 AD	29	−8.5 ± 0.4	9.2 ± 0.5	Hou et al. (2021a)
Nalintaohai	8 to 220 AD	7	−10.0 ± 0.8	13.3 ± 1.2	Zhang et al. (2012)

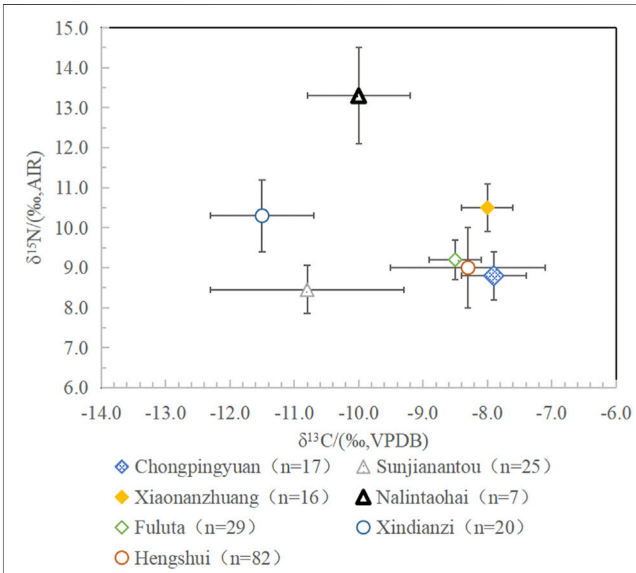

FIGURE 7 | The error bar plot of human bones around Northern Shaanxi.

relatively low, only slightly higher than that of Sunjiannantou people, and slightly lower than people of Hengshui and Fuluta (Ling et al., 2010; Sun, 2019; Hou et al., 2021a). Meanwhile, the people of Nalintaohai, Xindianzi, and Xiaonanzhuang had significantly higher $\delta^{15}N$ values than other people, indicating that they consumed more animal protein and were more engaged in nomadic life (Zhang et al., 2006; Zhang et al., 2012; Tang et al., 2018). The analysis indicated that, from the Eastern Zhou Period to the Qin and Han Dynasties, some people in northern China turned to nomadic life from agriculture, like Nalintaohai, but major people around the Great Wall area remained with their millet-based economy with animal husbandry as supplements. Although these regions also had a certain proportion of animal husbandry, their animal husbandry was dependent on their millet agriculture.

As previous studies show, during the Eastern Zhou Dynasty, multiple ethnic groups surrounded the Great Wall area, which was also an agro-pastoral ecotone. Due to ethnic habits and culture, people in these regions chose different subsistence strategies. The people close to the Huns (Xindianzi, part of Xiaonanzhuang) were more inclined to be nomads while the people of the Central Plain in Guanzhong area (Sunjianantou) were mainly engaged in millet agriculture. Apart from representative agriculture and nomadic life, people living on the cultural borders (Chongpingyuan, Hengshui) lived on agro-pastoral economies, which were mainly engaged in millet agriculture and supplemented by animal husbandry, which was attached to agriculture. Until the Qin and Han Dynasties, due to the dynasty expansion, the southern agricultural population migrated to the Loess Plateau, but these new immigrants chose the same subsistence strategies as the previous indigenous people. The impact of the natural environment on the subsistence strategies exceeded that of ethnicity and culture.

CONCLUSION

From the results of stable carbon and nitrogen isotope analysis of people and burial animals in the Chongpingyuan site in northern Shaanxi during the Eastern Zhou Dynasty, several conclusions can be drawn. The subsistence strategies of the Chongpingyuan people are agro-pastoral economics. Individuals mainly consume C_4 plants (millet), and domestic animals (pigs) fed on C_4 products. Cattle, sheep, and horses are not the main source of animal protein. There are no significant differences between genders and funeral customs, but people with abundant burial objects consumed more animal protein, showing possible class divisions.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

CM, SX, and HY conceived the project. CM conducted data analysis. All authors shared ideas, contributed to the interpretation of the results, and to the writing of the manuscript.

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First Documented *Camelus knoblochi* Nehring (1901) and Fossil *Camelus ferus* Przewalski (1878) From Late Pleistocene Archaeological Contexts in Mongolia

Alexey M. Klementiev[1,2], Arina M. Khatsenovich[1]*, Yadmaa Tserendagva[3], Evgeny P. Rybin[1], Dashzeveg Bazargur[3], Daria V. Marchenko[1], Byambaa Gunchinsuren[3], Anatoly P. Derevianko[1†] and John W. Olsen[1,4†]*

[1]Institute of Archaeology and Ethnography SB RAS, Novosibirsk, Russia, [2]Institute of the Earth's Crust SB RAS, Irkutsk, Russia, [3]Institute of Archaeology MAS, Ulaanbaatar, Mongolia, [4]School of Anthropology, University of Arizona, Tucson, AZ, United States

Edited by:
Shuangquan Zhang,
Institute of Vertebrate Paleontology and Paleoanthropology (CAS), China

Reviewed by:
Vadim Titov,
Southern Scientific Center (RAS), Russia
Wei Dong,
Institute of Vertebrate Paleontology and Paleoanthropology (CAS), China

***Correspondence:**
Alexey M. Klementiev
klem-al@yandex.ru
Arina M. Khatsenovich
archeomongolia@gmail.com

†These authors have contributed equally to this work and share senior authorship

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Throughout the arid lands of Africa and Eurasia, camelids facilitated the expansion of human populations into areas that would not likely have been habitable without the transportation abilities of this animal along with the organic resources it provides, including dung, meat, milk, leather, wool, and bones. The two-humped, Bactrian, species of *Camelus*, *C. ferus* in its wild state and *C. bactrianus* when domesticated, is much more poorly known in prehistoric archaeological contexts than its single-humped congeneric, *C. dromedarius*. Our research uses a convergence of evidence approach to analyze reports and remains of Plio-Pleistocene camelids in Central and Northern Asia and trace the latest-known fossil Bactrian relative, *Camelus knoblochi*, that seems to have survived in the Gobi Desert until the Last Glacial Maximum (ca. 26.5–19 ka). Rock art depictions, some of which may be of Pleistocene age, record the complexity of nascent human-camel interactions and provide the impetus for further archaeological studies of both the origins of *C. bactrianus* and its increasingly complex relationships with the highly mobile prehistoric peoples of Central and Northern Asia.

Keywords: paleontology, taxonomy, eastern Central Asia, Mongolia, pleistocene, Camelus knoblochi, human-animal interactions

1 INTRODUCTION

Camelus knoblochi was the largest of the Pleistocene Eurasian Bactrian (two-humped) members of the genus *Camelus*. The broad zoogeographic range of their remains has made this extinct tylopod the *fossile directeur* of Middle Pleistocene Khazar and Singil mammalian complexes in the northern Caucasus, Volga and Caspian basins, Tajikistan, Kazakhstan, and southern Siberia, including Transbaikalia (the mountainous region east of Lake Baikal) (Titov 2008). *C. knoblochi* remains are also known from loess deposits in the Ordos Region in northern China (Boule and de Chardin 1928; Qi 1975; Yamanaka 1993; Dong et al., 2014). Although the Ordos Region and the Altai Mountains in Kazakhstan and Russia have yielded multiple fossils of *Camelus knoblochi* (Kozhamkulova 1963; Vasiliev 2016), this camelid has not been previously reported from Mongolia. Joint Mongolian-Soviet and Mongolian-Russian-American expeditions ongoing since

1985 have recovered Middle and Late Pleistocene camelid fossils in Mongolia, but most such remains have not yet been published.

A brief history of *Camelus* finds reflects the growing data on Quaternary fossil faunas in Mongolia. The earliest and most complete description of a Mongolian camelid fossil is the *Camelus sivalensis* astragalus from the Ööshiin-Bor-Uzuur-Uul Member in the Öshiin Formation of the Dzeregen Valley in southwestern Mongolia (Belyeva 1937). *C. sivalensis* was first described by Falconer and Cautley (1836) based on remains from the Sivalik Hills in northern India. They concluded that this camel was similar to both modern Bactrian and dromedary species (Colbert 1935; Bibi and Métais 2016). The astragalus from Ööshiin is the only *C. sivalensis* fossil yet reported outside of India.

In the 1960s, a camelid metatarsal was found at the base of colluvial deposits at Bulan-Khujir near Ulaanbaatar (Okladnikov and Troitsky 1967), but further details are lacking. Similarly, E.V. Devyatkin published the discovery of Pliocene camel remains from Mongolia without accompanying detailed descriptions (Devyatkin 1981). These specimens were found at three localities: *Paracamelus* sp. from Khyargas Nuur 2, *P. gigas* from Yavar 1, situated in the Great Lakes Depression (Mong. *Ikh Nuuruudyn Khotgor*), in northwestern Mongolia, and *Camelus*? sp. from Orog Nuur (Orok Nor) in the Valley of the Lakes (Mong. *Nuuruudyn Khöndii*) in south-central Mongolia.

Khyargas Nuur 2 is a paleontological locality on the north shore of the eponymous lake in the Uvs Province, western Mongolia. The stratigraphic section includes three units; fossils of *Paracamelus* sp. were found in the upper part of Unit A (Layers 9–11, 37–61 m), together with several species of *Hipparion*, *Sinomegaceros* sp., *Antilospira* sp., *Olonbulukia* sp. (a stem-caprine species), *Canis* sp., and members of the Chalicotheriidae, among others (Devyatkin 1981). The Yavar 1 locality is situated in the Dzabkhan River Valley, near Khyargas Nuur. A variety of fossil remains were found there, including those of *Paracamelus gigas,* various species of *Hipparion*, and members of the Felidae, Bovidae, Cervidae, Giraffidae, and Mustelidae among others. Finally, a locality yielding *Camelus* sp. remains was recorded near Orog Nuur, in the Valley of the Lakes, in association with remains of *Hipparion* spp., *Gazella* sp., *Castor* sp., and *Struthiolithus* sp. along with members of the Rhinocerotidae and Mastodontidae (Berkey and Morris 1927; Devyatkin 1981). All these fossils are associated with Pliocene deposits. Some researchers consider these faunal assemblages to be Middle Pliocene, pre-Villafranchian (Vangengeim 1977; Devyatkin 1970, Devyatkin 1981) and are distributed throughout Mongolia, northeastern China, and northeastern Kazakhstan (Devyatkin et al., 1968; Vangengeim et al., 1972; Devyatkin 1981; but see; Ravsky et al., 1964).

From the Middle Pliocene through the late Holocene when domesticated Bactrian camels spread throughout Central Asia, especially during the Bronze Age, there is a gap in camelid evolutionary history in Mongolia. Obviously, the Camelidae occupied this vast region during the Pleistocene, but their remains have not previously been reported or published. In 1985, V.T. Petrin found fossil remains of large mammals at Tugrug Shireet in Ömnögovi Province, southern Mongolia. Our analysis of these remains revealed both fossil horses and camels. Remains of fossil camels were also mentioned in a description of deposits in the Uvs Nuur Basin in northwest Mongolia. The Chusutuin Gol section is situated in the Khustyn Gol Valley and includes deposits with mammalian remains going back to the beginning of Marine Isotope Stage 3 (48.3–45.3 ka BP) (Grunert et al., 2000), corresponding to a rise in the level of Uvs Nuur. These two camelid specimens have only been recently reported and never taxonomically identified or described in detail. A single find of *Camelus ferus* has been reported from Otson Tsokhio in the Gobi Desert, also without complete description (Janz et al., 2021).

2 MATERIAL AND METHODS

Here, we consider camelid remains recovered from two archaeological sites in Mongolia: Tsagaan Agui Cave and the Tugrug Shireet open-air site. Tsagaan Agui Cave is in Bayankhongor Province (44°42′53.3″ N, 101°10′13.4″ E; 2000 m asl) south-central Mongolia, in the Tsagaan Tsakhir limestone massif–part of the eastern Gobi Altai Mountains (**Figure 1**). The modern climate of the Gobi Altai Mountains is arid, and the Tsagaan Tsakhir inselberg is in a desert to semi-desert zone. There is no readily accessible surface fresh water; local pastoral nomads exploit a network of wells. Wet years bring abnormally high amounts of rain that result in short-term flooding, turning the Gobi Desert green. Flora and fauna are dominated by desert and semi-desert adapted species. Although vegetation cover is poor (ca. 15–20 cm high for therophytes and a bit higher for perennials), various reptiles and rodents thrive there. Lagomorphs are represented by the pikas (*Ochotona* spp.) and tolai hare (*Lepus tolai*). Herbivores and predators also inhabit the Gobi Altai region, including argali (*Ovis ammon*) and Siberian ibex (*Capra sibirica*), Mongolian gazelle or dzeren (*Procapra gutturosa*), red fox (*Vulpes*), corsac or steppe fox (*Vulpes corsac*), dhole (*Cuon alpinus*), and grey wolf (*Canis lupus*). Modern herding activity focuses on sheep, goats, camels and, to a lesser extent, cattle and horses. At higher altitudes near Ikh Bogd Uul Mountain, yaks are herded.

The ecology of the of Gobi Altai is characterized not only by sparse vegetation cover and a lack of large herds of ungulates, but also by significant annual and daily temperature differentials, extremely arid conditions, and very strong winds–all at altitudes above 2000 m a.s.l. in the Tsagaan Agui area. Hypoxia generally does not negatively impact human health in dry continental climates below 3,000–3,500 m a.s.l., in comparison with wetter regions like the mountainous interior of the Kamchatka Peninsula in Russia's Far East. However, modern mountain medicine regards 2000 m a.s.l. as falling within the high-altitude rubric (defined as beginning at 1,500 m a.s.l.) (Young and Reeves 2002). Climatic conditions are harsh in the Gobi and even xerocoles can be negatively impacted by dehydration and excessive solar radiation as well as a dearth of potable water and strong winds that transport sand, injuring the eyes. Paleolithic humans also needed to adapt to harsh environmental conditions, but one of our goals here is to explore whether the Pleistocene

FIGURE 1 | Principal finds of fossil camels in eastern Eurasia.

Gobi Altai region was characterized by milder climatic and environmental conditions that were not significantly different from Mongolia's forest and steppe zones.

Tsagaan Agui Cave has been known as an archaeological site since 1972 when the Mongolian archaeologist, D. Dorj first collected artifacts there. A subsequent intensive excavation campaign in 1987–1989 led by A.P. Derevianko and Dorj investigated the cave's Entrance and Entrance Grotto (Vkhodnoy grot), where abundant faunal remains and archaeological materials were found (Derevianko and Petrin 1985; Martynovich 2002). From 1995 to 2000, the Joint Mongolian-Russian-American Archaeological Expedition carried out excavations in the Lower and Inner Grottos and Main Chamber of the cave (Derevianko et al., 2000a, Derevianko et al., 2000b), yielding data on paleoclimate, accumulation of cave deposits, chronology and lithic technology. The cave's stratigraphy comprises 14 layers; archaeological material has been found in Layers 1–13. The chronology of the cultural horizons was determined by radiocarbon and then-experimental ESR dating approaches. Layer 2 was dated to the Last Glacial Maximum–(QT?) 23,000–25,000 BP; for Layer 3 there is a series of radiocarbon dates (AA-23159; 26588; 26587; 23158; 26589) falling between 31–34,000 BP; Layer 4 is dated to (QT40 & 41) 44–59,000 BP (Derevianko et al., 2000a, Derevianko et al., 2000b, Derevianko et al., 2004).

We recommenced excavations at Tsagaan Agui Cave in 2021 to obtain samples for additional radiocarbon and OSL dates and other analyses. A one square meter excavation pit, designated 2021/2, was dug in the northern part of the Main Chamber (Khatsenovich et al., 2021), in which Layers 1-6, according to the stratigraphic sequence revealed in the 2000 *sondage*, were uncovered. The upper part of a large camelid metacarpal was found in Layer 4 (**Figure 2**). The floor of the cave also contains Pleistocene material, both bones and artifacts, exposed by the erosion of underlying layers and sometimes transported by human agency (primarily tourists and Buddhist pilgrims) from the Inner Grotto and cave meanders. A large mammalian astragalus was found in such context. Three more camelid bones were subsequently rediscovered in the curated 1988–1989 faunal collections, including a carpal IV + V from Layer 2B near a combustion feature, a tibia fragment from Layer 1 (apparently redeposited), and a calcaneus fragment from an undetermined layer.

A camelid second phalanx was found at Tugrug Shireet (N 44°13′49.6″, 103°16′24.2″ E; 2000 m asl) in the northern Gobi Desert (**Figure 1**). This bone, together with the other mammalian remains, are likely not associated with the mostly Neolithic archaeological remains at the site. Taxonomic identification of the Tugrug Shireet faunal assemblage and preservation of the bone indicate a Pleistocene age for this phalanx.

We analyzed five camelid bones from Tsagaan Agui Cave and one from Tugrug Shireet. Comparable samples of modern *Camelus bactrianus* were collected in the vicinity of Tsagaan Agui Cave. We reviewed published data on fossil camels from China, Kazakhstan and Siberia and employed logarithmic curves, applied earlier in the study of horses (Eisenmann et al., 1986) and bison (Vasiliev 2008), to better visualize these data. Phalanges of a modern domestic llama (*Lama glama*) sourced from the Irkutsk Zoo served as samples to create the baseline curves.

3 SYSTEMATIC PALEONTOLOGY

Suborder Selenodontia
Infraorder Tylopoda
Family Camelidae Gray, 1821
Subfamily Camelinae Gray, 1821
Tribe Camelini Gray, 1821

FIGURE 2 | Proximal metacarpal (MC III + IV) fragment of *Camelus knoblochi* from Tsagaan Agui Cave, Mongolia: 1 - proximal view, 2 - dorsal view, 3 - plantar view.

Genus *Camelus* Linnaeus, 1758
Camelus knoblochi Nehring, 1901

Material: Os carpal IV + V (Tsagaan Agui, 1989; Unit A16, Layer 2B), proximal left metacarpal (Tsagaan Agui, Pit 2021/2, Layer 4), distal epiphysis of right tibia (Tsagaan Agui, 1988; Unit B9, Layer 1), distal portion of right calcaneus (Tsagaan Agui, 1988; unit A5), right astragalus (Tsagaan Agui, 2021; cave floor).

3.1 Description and Comparison

The os carpal IV + V (Tsagaan Agui, 1989; Unit A16, Layer 2B) is very large with a transverse diameter of 41.5 mm, a width of 49.5 mm, and an anterior height at the dorsal portion of 28.6 mm (**Figure 3**: 1–2). Equivalent bones of modern domesticated camels in the Gobi Altai ($n = 5$) are significantly smaller with a transverse diameter ranging between 37.4–38.7 mm, widths falling between 35.6–44.7 mm, and anterior heights ranging from 22.1–24.8 mm. The facet for the scaphoid bone on the fossil specimen porrects (extends forward) more than in modern specimens and the posterior scrobiculus is much deeper. Based upon these parameters, these bones are assigned to *C. knoblochi* (Boule and de Chardin 1928) rather than *P. gigas*. *C. knoblochi* is distinguished from the latter by the shape of the upper articular surfaces for MCIII and MCIV (Zdansky 1926). These differences, as well as the assumed Pliocene age of known *P. gigas*, excluded the latter from further comparative analysis.

A proximo-dorsal metacarpal fragment (Tsagaan Agui, Pit 2021/2, Layer 4) derives from a large individual (**Table 1**; **Figure 2**). The width and transverse diameter of the proximal epiphysis is much larger than the metacarpal of modern Bactrian camels in the Gobi Altai region (**Table 1**). Based on these morphometric parameters, this bone correlates well with both *C. knoblochi* (Khaveson 1954; Vangengeim and Gerbova 1962) and *P. gigas*, but the latter differs in the shape of its upper articular surface for metacarpals III and IV (Zdansky 1926). This fact and its assumed Pliocene age exclude *P. gigas* from conclusive correlation.

The distal epiphysis of a camelid right tibia from Tsagaan Agui Cave (1988, Unit B9, Layer 1) exhibits a parallelepiped articular surface (**Figure 3**: 3); facets for the astragalus are located oblique to the primary axis of the bone. The facet for os malleolare is large and its anterior face is larger than the posterior. The width and transverse diameter of the distal epiphysis are 90.0 and 56.2 mm respectively; much larger than in the domesticated *Camelus bactrianus* (73.3–86.4 and 44.6–50.8 mm, respectively). The equivalent bone from Tsagaan Agui is slightly smaller than the *C. knoblochi* tibias from Sjara Osso Gol or Salawusu (Boule and Teilhard 1928), Zyryanovsk, Kazakhstan (Kozhamkulova 1963) and the Volga River Valley (specimen PIN 2348; Khaveson 1954).

The Tsagaan Agui astragalus (2021, cave floor) is massive and wide, with a width:length ratio of 73.6% (**Table 2**; **Figure 3**: 4–7). The bone's dorsal face is asymmetric, and the external crista is much higher than the internal. The cuboidal facet is large with a deep, rough pit. This astragalus is much larger than similar bones of modern camels, falling within the range of variability of *C. knoblochi*.

Metric data on a calcaneus from Tsagaan Agui (1988, Unit A5) are incomplete, because the bone is fragmented (**Figure 3**: 11). The width of the bone body is 30.6 mm; much larger than that of the modern Mongolian domesticated camel (19.0–24.4 mm), but less than that of the specimen of *C. knoblochi* from Zyryanovsk, Kazakhstan (Kozhamkulova 1963). The calcaneal facet for os malleolare is 23.5° oblique to the bone's major axis and the length and width of the facet are 40.2 and 26.8 mm, respectively. The width of the facet of the *C. knoblochi* calcaneus from Sjara Osso Gol is 26 mm (Boule and de Chardin 1928). The lateral bone surface exhibits a wide pit.

Camelus ferus Przewalski, 1878

Material: second phalanx of the hind leg (Tugrug Shireet 5, 1985, specimen 276) (**Figure 3**: 12–13).

3.2 Description and Comparison

The rugose surface for attaching major ligaments on the caudal surface of the bone's distal margin is significant and occupies roughly half of the diaphyseal length. Logarithmic curves, based on Brigg's logarithm for the ratio of measurements for the camelid second phalanx to phalanges of modern *Lama glama*

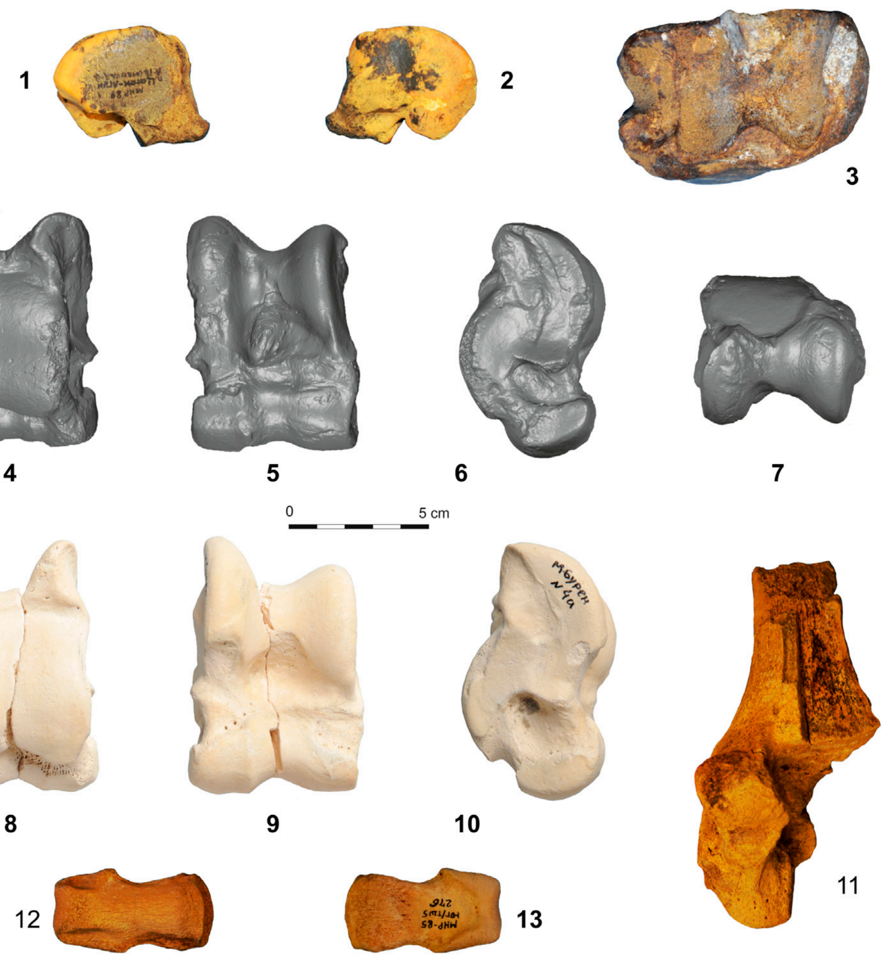

FIGURE 3 | Fossil camel bones from Central Asia: 1, 2–*Camelus knoblochi* carpal IV + V (distal and proximal view); 3–*Camelus knoblochi* distal tibia fragment (distal view); 4–7–*C. knoblochi* astragalus (dorsal, plantar, lateral and proximal views); 8–9–*Paracamelus* sp. astragalus (dorsal, plantar and lateral views); 11–fragmentary *C. knoblochi* calcaneus (view from the dorsal side); 12–13–*C. ferus* second phalanx of the hind leg (Sites: 1–7, 11–Tsagaan Agui Cave; 8–10–Mogen Buren; 12–13–Tugrug Shireet).

TABLE 1 | Measurements of camel metacarpals III+IV.

Metric data	***Camelus knoblochi*, Tsagaan Agui Cave, 2021**	***C. knoblochi*, Ust'-Kiran, Transbaikalia Vangengeim and Gerbova (1962)**	***C. knoblochi.* Volga, [from Khaveson (1954)**		***C. bactrianus*, Gobi-Altai, Mongolia**		***C. ferus* (Khaveson, 1954)**
	n = 1	*n* = 1	min-max (*n* = 4)	M	min-max (*n* = 8)	M	*n* = 1
1. Breadth of the proximal end	90.9	84.0	83.0-102.0	95.0	60.3-68.2	65.4	73.5
2. Depth of the proximal end	63.7	55.0	52.0-65.0	58.0	40.7-46.3	43.4	47.5
3. Sagittal depth of the proximal end	49.8	-	44.0-52.0	48.0	29.2-37.3	34.8	39.0
4. Depth of the facet for MC III	54.9	-	50.0-62.0	57.0	34.3-41.3	38.5	47.0
Indices, %							
2:1	70.1	65.5	58.6-63.7	61.1	63.3-72.3	66.4	64.6

TABLE 2 | Morphometrics of Central Asian camel astragali.

Metric data	***Camelus knoblochi*, Tsagaan Agui Cave, 2021**	***C. knoblochi*, Bukhtarma Cave, Altai** Vereshchagin (1956)	***Paracamelus* sp., Mogen Buren, Tyva**	***Paracamelus praebacrianus*, Kazakhstan,** Kozhamkulova (1963)		***Camelus bactrianus*, Gobi-Altai, Mongolia**		***C. ferus*** Khaveson, (1954)
	n = 1	*n* = 1	*n* = 1	min-max (*n* = 3)	M	min-max (*n* = 11)	M	*n* = 1
1. Greatest length	86.5	92.3	86.8	72.0-81.0	75.7	65.4-74.3	69.9	75
2. Medial length	81.9	85.5	78.8	67.0-80.0	73.3	60.8-67.9	65.2	70
3. Sagittal length	69.3	-	66.0	58.0-63.0	60.7	52.5-58.0	55.1	60
4. Maximal breadth	63.7	75.0	59.0	-	-	44.2-56.6	48.9	-
5. Distal breadth	59.8	-	57.0	51.0-55.0	52.7	43.5-53.8	46.7	55
6. Lateral depth	50.9	-	48.3	-	-	36.9-44.2	39.9	44
Indexes, %								
2:1	94.7	92.6	90.8	90.1-108.1	97.1	91.4-95.5	93.2	93.3
4:1	73.6	81.3	68.0	-	-	65.8-76.2	69.8	-

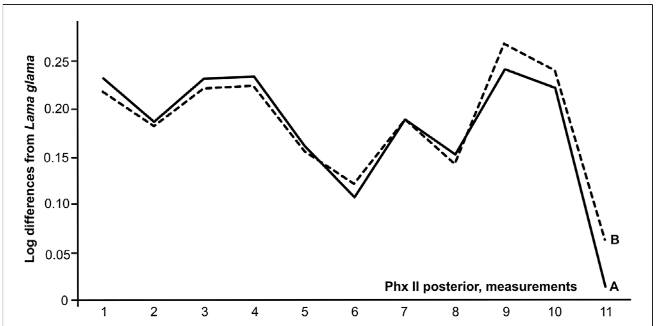

FIGURE 4 | Ratio diagrams of posterior second phalanges of *Camelus* from Mongolia: 1–Tugrug Shireet; 2–*C. bactrianus* (*n* = 6). Measurements: 1 - anterior length; 2 - posterior length; 3 - middle articular length; 4 - minimal articular length; 5 - breadth of the upper epiphysis; 6 - depth of the upper epiphysis; 7 - breadth of the diaphysis; 8 - depth of the diaphysis; 9 - greatest lower breadth; 10 - minimum breadth of the lower epiphysis; 11 - depth of the lower epiphysis.

yield similar curves for domesticated Bactrian and fossil camels from Tugrug Shireet (**Figure 4**). We included data on the first phalanx of *C. knoblochi* (Khaveson 1954; Vasiliev et al., 2015), and fossil *Camelus* remains from the Kamenka site in Transbaikalia (for which the authors determined genus, though not the species, of this camelid (Germonpre and Lbova 1996)), because equivalent data for the second phalanx of *C. knoblochi* are lacking. The diagram indicates the difference in phalanx length between *C. knoblochi* and Bactrian camels (**Figure 5**). The significant width of the fossil camelid first phalanx from the Kamenka site in Siberia allows it to be classified as *C. ferus,* which suggests that wild two-humped camels were latitudinally distributed from the Gobi Desert, north to western Transbaikalia in southern Siberia during the Late Pleistocene.

4 CAMELID EVOLUTION AND ZOOGEOGRAPHY IN EASTERN CENTRAL ASIA

Situated near the geographical center of Asia, Mongolia has played a pivotal role in the evolution and dispersal of many continental mammals, and various ungulate and carnivore groups appear to have originated there (Lopatin 2019). Although fossil camelid remains are scarce in Mongolia, we can conclude that they have existed there since the Pliocene. The oldest known camelid remains in Mongolia were found in the Pliocene Ööshiin Formation (Belyeva 1937) and further investigations carried out by the Mongolian-Soviet Complex Paleontological Expedition correlated this formation with the Altan-Teli Pliocene stratigraphic assise (Devyatkin 1981). The initial identification of these remains as *C. sivalensis* needs to be revised. It is likely that giant camelids, such as those described in China (Zdansky 1926) and Kazakhstan (Aubekerova 1974) also inhabited Mongolia during the Pliocene.

A subsequent camelid evolutionary link has been found in the Tyva Republic on the Russian-Mongolian border: a *Paracamelus*

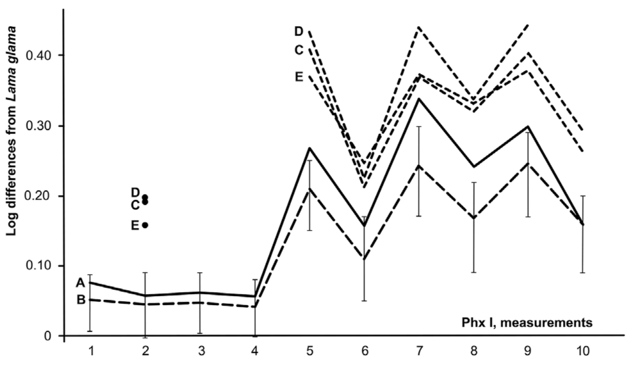

FIGURE 5 | Ratio diagrams of first phalanges of *Camelus* spp.: 1–Kamenka A; 2–*C. bactrianus* (n = 18; vertical lines indicate range of variability); 3, 4–*C. knoblochi* (Khaveson, 1954); 5–*C. knoblochi* (Vasiliev, 2011). Measurements: 1 - anterior length, 2 - posterior length, 3 - middle articular length, 4 - minimal articular length, 5 - breadth of the upper epiphysis, 6 - depth of the upper epiphysis, 7 - breadth of the diaphysis, 8 - depth of the diaphysis, 9 - greatest lower breadth, 10 - minimum breadth of the lower epiphysis, 11 - depth of the lower epiphysis.

sp. astragalus was recovered from Early Pleistocene deposits at Mogen Buren (Klementiev et al., 2021). The morphological features of this bone do not allow assigning it to the genus *Camelus* (**Figure 3**: 8–10), but its absolute size is characteristic of a smaller individual *C. knoblochi* (**Table 2**). This camelid specimen from Mogen Buren may represent a transitional stage of Pliocene *Paracamelus* spp. evolving into Pleistocene *Camelus knoblochi*. It is likely that camelid remains from the Kuruksai and Lakhuti deposits in the Afghan-Tajik Depression also represent intermediary forms, but there is a notable discrepancy in species identification. Sharapov defined a new species, *P. trofimovi*, based on all remains available at the time (Sharapov 1986). Alekseeva, considering the different ages of the Kuruksai and Kairubak stratigraphic assises, assigned camelid remains from Lakhuti 2 to *C. knoblochi* and from Lagernaya and Kuruksai to *P. praebacrianus* (Vangengeim et al., 1988).

The timing of the peak distribution of *C. knoblochi* and its prochoresis cannot be reconstructed directly from fossil remains in Mongolia, but the history of this species is known in eastern Europe and Kazakhstan as well (Titov 2008). The demonstrated presence of *C. knoblochi* in the Late Pleistocene of the Gobi Altai and Ordos regions and in China's Heilongjiang Province ("Manchuria") raises an important question regarding the age of sandy deposits in Transbaikalia and Mongolia. The chronology of the Ust' Kiran faunal complex in western Transbaikalia, including a bone of *C. knoblochi*, is based on long-held assumptions about the Early Pleistocene age of the sandy deposits there, based on faunal remains (Vangengeim and Gerbova 1962). According to chronometric dates for this formation, that have been skeptically received, sand deposits in the Selenga River Basin accumulated up to the end of the Pleistocene (Perevalov and Rezanov 1997). Finds of *C. knoblochi* in Late Pleistocene deposits in Tsagaan Agui Cave support these dates.

FIGURE 6 | Herds of modern domesticated *C. bactrianus* near Tsagaan Agui Cave in the Gobi Altai Region and Holboljin Nuur Lake in the Valley of the Lakes Mongolia (photos by A. M. Khatsenovich, 2021).

Additional finds are associated with the persistence of *C. knoblochi* in arid landscapes of the Gobi Altai region at the end of the Middle Pleistocene and in the Late Pleistocene. Camel remains were first identified at Tsagaan Agui Cave by N.D. Ovodov, but never published, although other faunal remains recovered from the cave were reported (Ovodov 2001). The nearest localities to Tsagaan Agui yielding Late Pleistocene *C. knoblochi* remains are in the Ordos Region (Yamanaka 1993) and Heilongjiang Province in North China (Yuan et al., in press). The wild Bactrian camel, *Camelus ferus*, also appeared in Central Asia during the Late Pleistocene at Tugrug Shireet in Mongolia and the Kamenka site in Transbaikalia. Limited data do not illuminate its phyletic links with ancestral species and its possible co-existence with *C. knoblochi*. Recent genetic data suggesting a ca. 300 ka origin for *C. knoblochi* (Yuan et al., in press) are at odds with its presence at Lakhuti 2, which is dated to the Early Pleistocene (i.e., >773 ka).

In the Middle Pleistocene, *C. knoblochi* co-existed with *Canis lupus, Mammuthus chosaricus, Stephanorhinus kirchbergensis, Elasmotherium sibiricum, Bison priscus longicornis, Saiga*

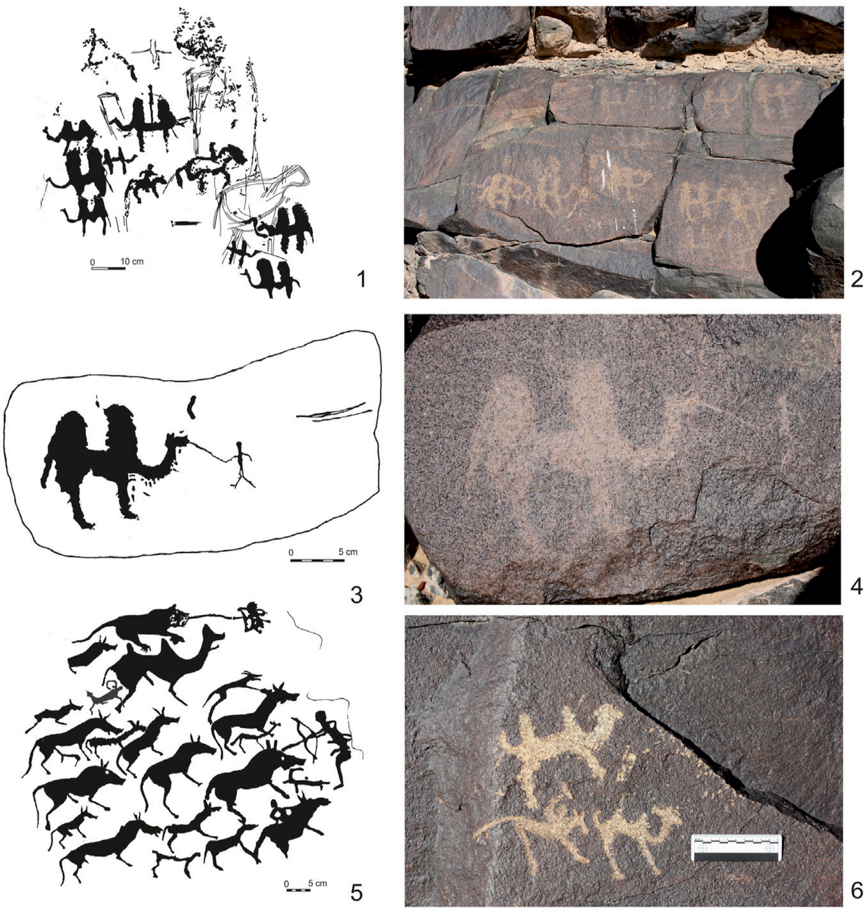

FIGURE 7 | Bronze Age camel petroglyphs in the Gobi Desert: 1–4–Ikher Gashuun, Noyon County, Ömnögovi Province; 5–Bichigtiyn-am, Bayanlig sum, Bayankhongor Province; 6–Zamyn Baruun Barsgai, Noyon County, Ömnögovi Province.

tatarica, Megaloceros giganteus and *Cervus elaphus*, a faunal association reflecting predominantly steppic conditions, and identifying *C. knoblochi* as an inhabitant of a steppe zone in the Volga River Basin (Titov 2008). Faunal remains from Late Pleistocene layers in Tsagaan Agui Cave include cave hyaena (*Crocuta spelaea*), khulan (*Equus hemionus*), argali (*Ovis ammon*), Siberian ibex (*Capra sibirica*), Mongolian gazelle or dzeren (*Procapra gutturosa*), Tibetan antelope or chiru (*Pantholops hodgsonii*), and tolai hare (*Lepus tolai*). These species, which did not become extinct at the end of the Pleistocene, are typical of modern steppe zones in Mongolia and high-altitude regions of Tibet. This faunal association indicates a dry steppe environment in the Gobi Altai during its occupation by both *Camelus knoblochi* and Paleolithic humans in the Late Pleistocene. The large body-size of this camel is evidence of abundant forage resources that are not characteristic of desert biomes.

Two finds of this fossil species in southwestern Siberia indicate its occasional association with forest-steppe landscapes during the Late Pleistocene (Vasiliev et al., 2015; Vasiliev 2018), perhaps indicating that, just prior to its extinction, *C. knoblochi* spread into unfamiliar and less salubrious ecological niches. Apparently, this species was poorly adapted to desert biomes, primarily because such landscapes could not support such large animals, but perhaps there were other reasons as well, related to the availability of fresh water and the ability of camels to store water within the body, poorly adapted mechanisms of thermoregulation, and competition from other members of the faunal community occupying the same trophic niche. Both wild and domesticated modern Bactrian and dromedary camels are xerocole species highly adapted to desert conditions based on genomic studies of insulin resistance, salt tolerance (Wang et al., 2012; Burger and Palmieri, 2013), fat metabolism, stress responses to arid environments, thermo- and osmoregulation, changes in respiratory systems and other biological factors (Wu et al.,

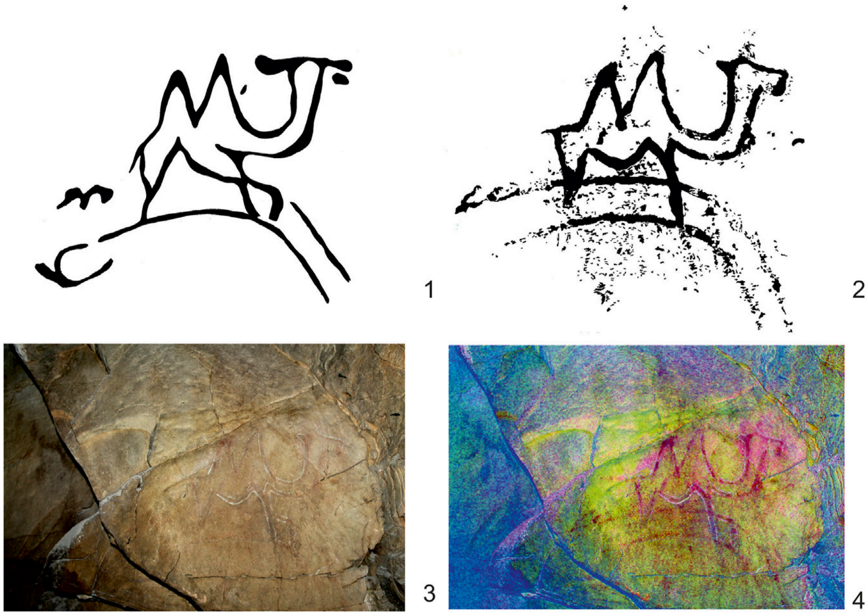

FIGURE 8 | Purportedly Paleolithic image of a camel in Khoid Tsenkheriin Agui Cave, Mongolian Altai: 1–widely published drawing by Academician A.P. Okladnikov in the 1970s (Okladnikov 1972); 2, 3, 4–drawing made from a photograph taken for this study and enhanced in iDStretch (version 2.2., created by Jon Harmon).

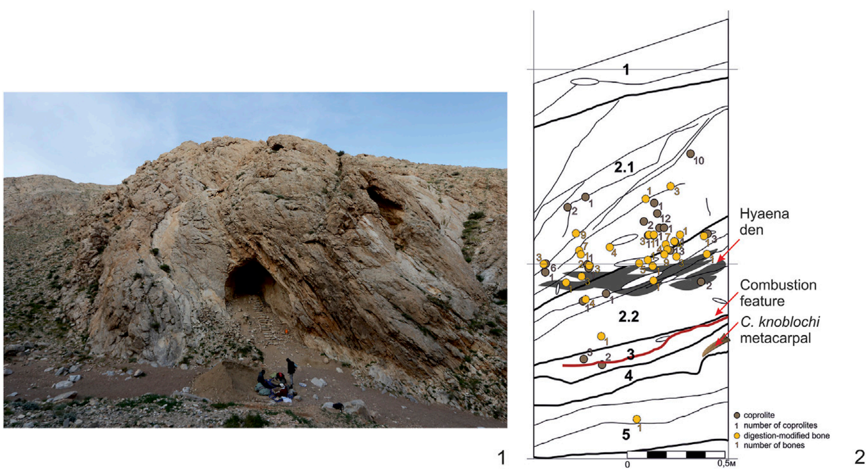

FIGURE 9 | Evidence of human-animal interaction at Tsagaan Agui Cave, Gobi Altai Region, Mongolia: 1 – view of the cave; 2 – cross-section of Pit 2021/2 indicating hyaena dens, coprolites and the position of *C. knoblochi* metacarpal in Layer 4.

2014). But it is unknown whether *C. knoblochi* expressed any of those adaptive mechanisms. Tsagaan Agui Cave contains some of the latest evidence of the presence of *C. knoblochi* in a steppe biome just prior to its extinction. Considering the age of Tsagaan Agui Layer 4, where a camelid cannon bone was found in an undisturbed deposit (59,000–44,000 BP; Derevianko et al., 2000b) and characteristics of the associated archaeological complex and the presence of a bone tool industry (Khatsenovich et al., 2021) that implicitly support this age, camels occupied the Tsagaan Agui region during MIS 3. Pollen analysis indicates increasing aridification and cooling throughout this period, in comparison with underlying layers, with predominant grasses and shrubs in the pollen spectra as well as small quantities of spruce (*Picea*), pine (*Pinus*), and birch (*Betula*) (Derevianko et al., 2000b). The last *C. knoblochi* were present at Tsagaan Agui probably during the Last Glacial Maximum (ca. 26.5–19 ka), the presumptive age of Layer 2, determined

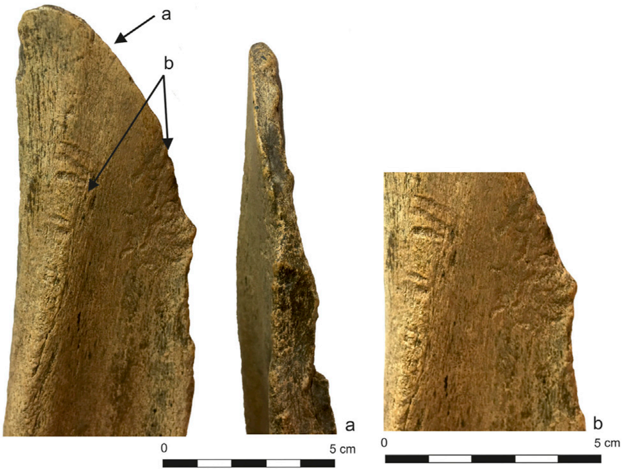

FIGURE 10 | *C. knoblochi* metacarpal from Tsagaan Agui Cave, Layer 4 exhibiting traces of anthropogenic splitting with hyaena gnawing above.

by ESR in the late 1990s (Derevianko et al., 2004). This was a period of increasing aridification when semi-desert landscapes likely replaced steppe biomes.

5 CAMEL-HUMAN INTERACTIONS

Domesticated camels have played a pivotal role in human societies inhabiting arid zones in both prehistoric and historic times. Camels can carry significant burdens over long distances and are the source of organic resources including dung, meat, milk, leather, wool, and bones (**Figure 6**). The significance of this domesticated animal is documented by numerous petroglyphs occurring throughout arid zones of Mongolia since the Bronze Age. One example includes camels depicted on dark rocks at Ikher Gashuur, in the southern Gobi Desert, that have very tall and thick humps, sometimes higher than the length of the animals' legs (**Figure 7**). They are often depicted in herds, sometimes accompanied by people riding horses or other camels (**Figure 7**: 1–2). Another common rock art motif is the image of a human leading a camel (**Figure 7**: 3–4) and, less commonly, people protecting camels from their natural enemies (**Figure 7**: 5). All such petroglyphs reflect close relationships between humans and domesticated camels, but there is also rarer petroglyphic evidence of human interactions with wild camels. In such rock art panels, *C. ferus* is portrayed with small, often triangular humps, compared with their domesticated counterparts. One such depiction occurs at Zamyn Baruun Barsgai in Noyon County, Ömnögovi Province in which a person on horseback fends off a morphologically wild camel with a hatchet to protect an apparently domesticated camel (**Figure 7**: 6).

The only known presumed Paleolithic image of camel is a pictograph in Khoid Tsenkheriin Agui Cave in the Mongolian Altai Mountains of Mankhan County, Khovd Province (Okladnikov 1972; Novgorodova 1984). There, several animals, including mammoths and ostriches, were painted as realistic contour images on walls inside of the cave with red and brownish red organic pigments. These realistic images are regarded as having been painted in the so-called "Kalgutinsky style," distinct from images typical of later Neolithic and Bronze Age rock art (Molodin et al., 2019; but see; Miklashevich 2020). This fact, and the depiction of Pleistocene animal species, suggest that these associated images of mammoths, camels and ostriches are of Pleistocene age. One widely known image was redrawn and published by Okladnikov (1972): a walking camel appears full-faced with distinct ears and a thickly outlined body (**Figure 8**: 1). Landscape is depicted under its feet. A recent photo, taken by one of us (Y.Ts.) in Khoid Tsenkheriin Agui Cave, and enhanced in iDStretch (version 2.2 created by Jon Harmon) (**Figure 8**: 3–4), suggests that the camel's head is depicted in profile, exhibiting only a small right ear (**Figure 8**: 2). The landscape depicted under the animal's legs more closely resembles a hill.

Evidence of human-camel interactions can also be detected in analyzed bone samples from archaeological contexts, including the *Camelus* metacarpal from Tsagaan Agui Cave Layer 4. This large bone was flaked by human agency, probably to access the bone's marrow cavity: it was intentionally split with negative conchoidal fractures apparent on the proximal epiphysis (**Figure 2**: 2). The other end of the bone was utilized after having been split; it exhibits negative scars of spall removals, most likely unintentional, on the narrow side of the fracture (**Figure 9A**). It is difficult to determine if this animal was hunted or scavenged by humans, but we know that cave hyaenas (*Crocuta spelaea*), notorious scavengers whose abundant coprolites were found in Tsagaan Agui Cave Layers 2-5, occupied the grotto concurrently with or closely following the human presence there (**Figure 10**: 1–2). Traces of hyaena gnawing are visible on this metacarpal above the anthropogenic damage apparent on the bone (**Figure 9B**).

CONCLUSION

The results of our study help fill the chronological gap between Pliocene *Paracamelus* spp. and Holocene wild camels in Mongolia. They indicate that *Camelus knoblochi* occupied eastern Central Asia to the end of the Pleistocene and inhabited mainly steppe biomes, expanding to forest-steppe zones near the time of its extinction, which was most likely the consequence of increasing aridification of its natural habitat. The latest known regional evidence of *C. knoblochi,* as well as *Crocuta spelaea*, occurs in Tsagaan Agui Cave, Layer 2, presumably dating no earlier than the Last Glacial Maximum (ca. 26.5 ka). The wild Bactrian camel, *Camelus ferus*, appeared in Mongolia during the Late Pleistocene, and it is possible this species was already adapted to harsh desert environments which may have further reduced the geographic range of *Camelus knoblochi* through competitive exclusion. Camels played a pivotal role in human adaptations in historic and, likely, Paleolithic times as well. Because modern *Camelus ferus* exhibits genetic differences from modern domesticated *C. bactrianus* in Mongolia, the latter of whose ancestry is still poorly understood, intriguing possibilities for the study of *Camelus knoblochi* and its relationship to both *C. ferus* and, ultimately, *C. bactrianus* emerge.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because We studied fossil remains of extinct Pleistocene species.

AUTHOR CONTRIBUTIONS

AKh, JO, AD, ER, BG designed research; AKh, AK, JO, ER, BG, DB, and YT performed research; AK, AKh, JO, YT, and DM analyzed data; AK, AKh, JO, and YT wrote the paper.

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Pig Management Strategies in the East Liao River Basin From the Bronze Age (c. 2000–256 BC) to the Liaojin Dynasties (907–1234 AD): Stable Isotope Analysis of Animals at the Changshan Site, Jilin Province, China

Xiaohong Lv[1], Lin Ban[1], Yiwen Liu[1], Ying Guan[2], Hailin Liu[1], Chunxue Wang[1] and Liangliang Hou[3,4,5]**

[1]Bioarchaeology Laboratory in School of Archaeology, Jilin University, Changchun, China, [2]Key Laboratory of Vertebrate Evolution and Human Origin, Institute of Vertebrate Palaeontology and Palaeoanthropology, Chinese Academy of Science, Beijing, China, [3]Department of Archaeology, School of History and Culture, Shanxi University, Taiyuan, China, [4]Department of Cultural Heritage and Museology, Fudan University, Shanghai, China, [5]Institute of Archaeological Science, Fudan University, Shanghai, China

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***Correspondence:**
Chunxue Wang
chunxuewang@jlu.edu.cn
Liangliang Hou
llhou@sxu.edu.cn

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Pig domestication and management strategy has been increasingly discussed in recent years, focusing on the temporal-spatial differences of pig management strategies. The East Liao River Basin with diverse ecosystems, cultural exchanges, and collisions plays an important role in the cultural development, exchange, and integration processes between Northeast China and the Central Plains. Multiple studies have revealed that various forms of subsistence economy, such as nomadism, fishing and hunting, and farming, existed in this region. However, no report or discussion has been presented concerning the status of domestic animal management strategies over a long-term in the East Liao River Basin. Carbon and nitrogen stable isotopes analysis were performed on the fauna bones at the Changshan site in Siping, Jilin, China, from the Bronze Age (c. 2000–256 BC) to the Liaojin Dynasties (907–1234 AD), to reconstruct their dietary pattern and reveal the status of domestic animal management strategies, especially the diachronic changes in pig feeding strategies. The results showed that pigs (–19.3 ± 1.6%, 5.3 ± 0.9%, $n = 27$), horses (–18.4 ± 1.7%, 4.8 ± 1.4%, $n = 7$), and sheep (–19.8 ± 1.5%, 5.7 ± 0.5%, $n = 6$) primarily received their subsistence through C_3-based food. Nevertheless, cattle (–16.4 ± 3.5%, 6.0 ± 2.1%, $n = 2$) and the past human (–13.9%, 10.3%, $n = 1$) lived on mixed C_3/C_4-based food. Notably, the stable isotope data for pigs from the Bronze Age (–19.1 ± 2.0%, 5.4 ± 1.0%, $n = 9$) to the Liaojin Dynasties (–19.8 ± 0.6%, 5.1 ± 0.7%, $n = 15$) were similar, indicating that the management and/or feeding strategy of domestic pigs were relatively stable with a free range in a wild ecosystem over a long period. Related studies have shown that pigs in captivity were mainly fed by millet-based food in the West Liao River Basin and the middle reaches of the Yellow River valley, where millet agriculture were adequately developed. Abundant natural resources, including plants, wild animals, and fishes, could provide sufficient food to the past population in the East Liao River Basin. Thus, the millet-based agriculture was just an auxiliary subsistence strategy in the Changshan site, leading to a gap in the driving force for long-term intensive management of pig.

Keywords: The East Liao River Basin, Changshan site, carbon and nitrogen stable isotopes, pig management strategy, free-range

INTRODUCTION

The domestication of pigs resulted in the widespread adoption of pigs as meat resources worldwide, especially in China. Today there are more than one billion pigs worldwide. 'Each place has its own way of supporting its own inhabitants', and the past human and animals in different temporal-spatial environments relied on various natural resources, which resulted in huge differences in subsistence patterns. This was similar to pig management strategy.

Multiple studies have revealed that the utilization of millets by domestic dogs was detected at the Nanzhuangtou site, around 10,000 years ago (Yuan and Li 2010; Hou et al., 2021). However, no evidence was found regarding domestic pigs during this period in China. Pigs with direct signs of domestication were found in Jiahu site around 9,000 years ago (Luo 2012). Thereafter, pig became an important animal in the Neolithic period (Song, 2012). Based on the millet-based agriculture, the past populations fed pigs at many current archaeological sites, such as the Dadiwan (Qi et al., 2006), Peiligang (The Institute of Archaeology, Chinese Academy of Social Sciences 1996), Cishan (Zhou 1981; Yuan, 2001), and Xinglonggou (Dong et al., 2007; Zhang et al., 2017) sites, around c. 6,000 BC–5,000 BC, in the middle portions of the Yellow River valley and the West Liao River Basin. The domestic pigs were placed at the bottom of the pits at the Cishan site, indicating that millet growth had developed to the extent that it could sustain pigs feeding at that time (Tong 1984). Under the millet-based agricultural background, pig feeding strategies were obvious in northern China from the Neolithic Periods to the Bronze Age (e.g., Guan et al., 2011; Hou 2019). In other words, captive pigs were fed with millet-based food, including millet and/or millet by-products, table scraps, and human faeces.

Different pig management strategies were also observed in the Huai River valley (e.g., Dai and Zhang 2021), the Yangtze River Basin (e.g., Guan et al., 2008; Guo et al., 2011; Zhang et al., 2015; Guan et al., 2019; Dong and Yuan 2020; Yuan et al., 2020; Hongo et al., 2021; Hu 2021), and the Pearl River (e.g., Wang, 2018Wang, 2018; Liu et al., 2021), as well as the beach area (Wang et al., 2011). Multiple lines of evidence have revealed that the past populations in southern China preferred wild resources supplemented by the limited exploitation of domestic pigs (Dong and Yuan 2020; Yuan et al., 2020; Hongo et al., 2021). Consequently, the driving force for intensive management of domestic pigs was inadequate, with most pigs being free-range and fed in the wild ecosystem (Dong and Yuan 2020). With the development of rice-based agriculture in the above regions, the pigs started receiving rice-based food, including rice by-products, table scraps, and even human faeces (e.g., Guan et al., 2011; Hou 2019). However, wild plants and rice belong to C_3 plants, with a low $\delta^{13}C$ average (−26.5‰) (Ambrose 1991). Thus, we could not detect the extent of rice-based food consumption in pig diets. Notably, heavy dependence on rice-based food protein leads to an increase in the $\delta^{15}N$ value of animal tissues (e.g., Guan et al., 2007; Hu et al., 2009). Thus, the $\delta^{15}N$ values could help detect the feeding strategies in southern China.

The extent and status of the development of agriculture in the East Liao River Basin remains ambiguous, including the status of pig management strategies. The East Liao River Basin (**Figure 1**) contains rich relics of human activities dated as early as the Neolithic Age. For example, in the Houtao Muga site, which is a Neolithic archaeological site (c. 4500–3000 BC), faunal bones were dominated by large and medium-sized mammals (e.g., pigs, dogs, cattle, sheep, and deer), while large numbers of birds and fishes were also present (Wang et al., 2017; Liang et al., 2020; Song et al., 2017; Tang et al., 2017a). Wild faunal bones (e.g., Mongolian rabbits, ring-necked pheasants, wild boars, Przewalski's gazelle, and fish) and domestic dogs (Zhang et al., 2012) were found in the Shuangta site (c. 3500–3000 BC). Clearly, a broad-spectrum subsistence economy consisting of hunters and gatherers was predominantly observed in this region, and the previous populations primarily relied on abundant natural resources. In the Bronze Age (c. 2000–256 BC), numerous archaeological sites and animal remains were found in the East Liao River Basin. Domestic pigs were first found at the Dawangshan site (c. 2000–1000 BC) (Fan et al., 2014; Zhang et al., 2012; Tang et al., 2017b) and Wangqing River site (c. 2000–500 BC) (Song and Chen 2016) among various animal assemblages (e.g., red deer, roe deer, wild boar, birds, pigs, dogs, and sheep), indicating that pig feeding was only an auxiliary subsistence strategy. In the Liaojin Dynasties (907–1234 AD), at the Yinjia Wobao site, the proportions of animal bones of fish and mammals were 34.0 and 31.0%, respectively, indicating that fishing and hunting economy remained a dominant secondary strategy in this region (Shi et al., 2017; Liang et al., 2018). However, agricultural tools, such as iron sickles, saws, and axes were also found at the Aodongcheng site (Wang et al., 2006), which is located close to and is contemporary with the Yinjia Wobao site, indicating that the development of agriculture also followed an auxiliary subsistence strategy. It should be noted that the cultural sequence of the Wanfa Bozi site (**Figure 1**) is successive (Jilin Provincial Institute of Cultural Relics and Cultural Relics Management Office of Tonghua 2019), covering a period from the Neolithic period (c. 4000–2000 BC) to the Ming Dynasty (1368–1644 AD). Based on archaeological assemblage's research, it can be concluded that hunting-gathering-fishing was the primary subsistence strategy at this site (Yu and Jin 2018). Meanwhile, pigs were also fed by the past populations for the supplementary meat recourses from the Bronze Age (c. 1600–256 BC) (Tang et al., 2006). Guan et al. (2007) were the first to report pig isotopic results at the Wanfa

FIGURE 1 | Map of mainland China showing the location of the Changshan site in Jilin Province and the additional archaeological sites mentioned in the text (Original Image Source: http://bzdt.ch.mnr.gov.cn) (1. Changshan site, 2. Wanfa bozi site, 3. Xinglonggou site, 4. Xinzhai site, 5. Erlitou site, 6. Taosi site, 7. Zhangdeng site).

Bozi site in the East Liao River Basin during the historical period. Their results found the diet of pigs with more protein compared with those of wild boar. While this is regarded as pioneering research, it was limited in scope by just distinguishing between wild boar and domestic pigs (Guan et al., 2007).

Finally, the utilization of natural resources with a broad-spectrum economy was a dominant strategy in the East Liao River Basin over a long-term, starting from the Neolithic Age (c. 4500–3000 BC) and the Bronze Age (c. 2000–256 BC) to the Liaojin Dynasties (907–1234 AD), and a small amount agricultural economy was also detected.

After carefully considering these existing achievements in the East Liao River Basin, we found at least two problems. First, no report or discussion has been found concerning the status of pig management strategies systematically. What was the role of pigs in people's lives? Second, no research has constructed a systematic discussion over an extended period. Was there any change in pig management strategy over a long-term, especially with the continuous influence of agriculture development?

In this study, we conducted a stable isotope analysis of faunal remains from the Changshan site (Lin et al., 2018), from the Bronze Age (c. 2000–256 BC) to the Liaojin Dynasties (907–1234 AD), to reconstruct their diet and management strategies. The isotopic data was compared with previously published data from the central plains and Northeast China in the Bronze Age (c. 2000–256 BC) and historical periods (Guan et al., 2007; Chen et al., 2012; Hou et al., 2013; Dai et al., 2016; Zhang et al., 2017) to better understand pig management strategies in the East Liao River Basin.

ARCHAEOLOGICAL CONTEXTS

Archaeological Background

The Changshan site (43°44′ E, 124°25′ N) is located in the Changshan village, Lishu county, Siping city, Jilin Province, the average altitude is about 160 m and it is located 1,000 m from the East Liao River in the north (**Figure 1**).

In 1983, the Changshan site was discovered at the census of cultural relics (Jilin Province Cultural Relics Editing Committee 1984). Two systematic excavations were conducted in 2016 and 2017. The total excavated area was up to 3,225 square metres. A total of 378 ash pits, 18 ash ditches, 19 tombs, and 23 houses were discovered. Additionally, 33 pieces of pottery were restored, and nearly 2,300 pieces of stone-bone clams and metalware were studied (Lin et al., 2018). Abundant stoneware, pottery, and faunal remains were found, dating to the Neolithic Period (c. 4000–2500 BC), the Bronze Age (c. 2000–256 BC), and Liaojin Dynasties (907–1234 AD) (Lin et al., 2018). The excavated area in 2016 was about 975 square metres (**Figure 2**), and the faunal bones studied in this research were selected from this area.

Zooarchaeolical Analysis

Numerous faunal remains were unearthed at the Changshan site, around 30 specimens, including pigs [number of identifiable specimens (NISP = 297)], horses (NISP = 94), cattle (NISP = 38), sheep (NISP = 14), goats (NISP = 11), deer (NISP = 169), dogs (NISP = 97), fish (NISP = 116), birds (NISP = 123), frogs (NISP = 1380), and shells (NISP = 90). Preliminary studies have shown that domestic pigs and dogs had already existed at that time.

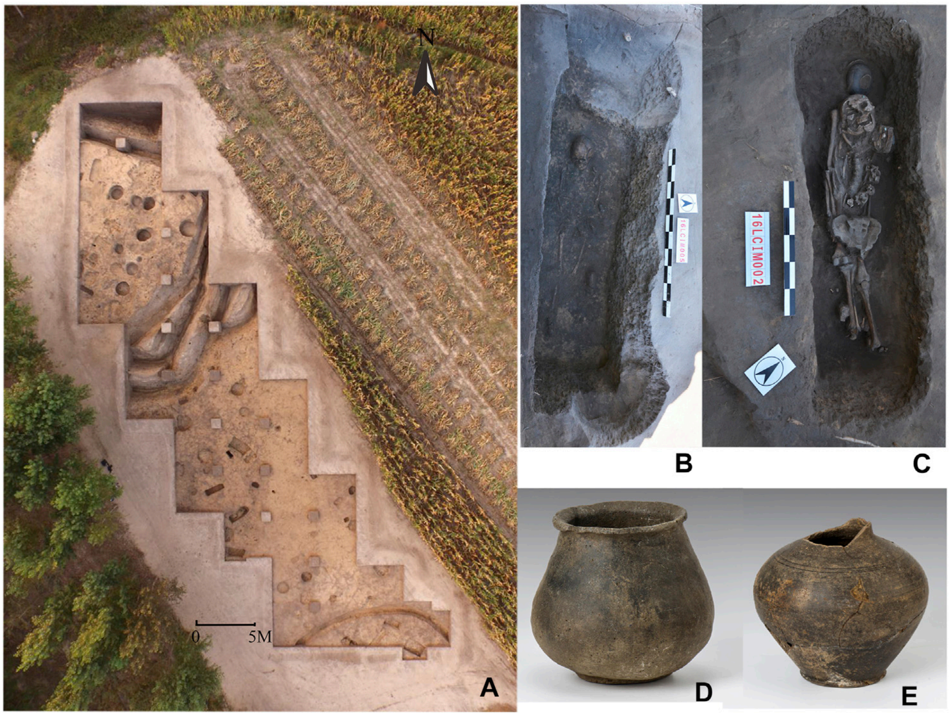

FIGURE 2 | (A) aerial photograph of the excavation area of the Changshan site in 2016 **(B)** picture showing top view of the burial of one Bronze Age individual **(C)** a pottery vessel in the Bronze Age **(D)** picture showing top view of the burial of one Liaojin Dynasties individual **(E)** A pottery vessel in the Liaojin Dynasties.

This study focused on identification of pigs using traditional morphological observations and biometric measurements. The number of pigs unearthed at the site (NISP = 297) accounts for 34.3% of all mammals. To clarify the nature of the pigs at the site, the sizes of the pig teeth, ages of death, and levels of linear enamel hypoplasia (LEH) were also conducted. A total of 73 identifiable specimens of pig bones was unearthed that date to the Bronze Age (NISP), and the minimum number (MNI) of pigs was four; the number of identifiable specimens of unearthed pig bones that date to the Liaojin Dynasties (NISP) was 218, and the minimum number (MNI) of pigs was six. Given the distribution of the bones in pits excavated from different areas of the site, it is likely that more than 10 pigs are represented in the study sample.

Only one lower M3 dated to the Bronze Age measuring 38.06 mm in size, and four lower M3 in the Liaojin Dynasties measuring 41.21, 39.18, 39.98, and 38.54 mm in size are all less or similar to 39.00 mm, which is the current domestic pig standard size (Guan 2008; Luo 2012; Zhang and Julia, 2019), indicating that these pigs were likely domestic pigs. There were certain amounts of linear enamel hypoplasia (LEH) observed in both the Bronze Age and the Liaojin Dynasties, and the incidence of LEH in the Bronze Age was relatively high (Luo 2017). Additionally, eight canine teeth were found, including seven female and one male (Luo 2017). The age of death was mostly found to be in the same range at 18–24 months (Luo 2017), indicating that the past populations obtained meat resources by killing the pigs in the optimum time.

MATERIALS AND METHODS

Sampling Strategy

In this study, 52 bones samples (**Table 1**) were used, including 35 pigs, eight horses, two cattle, two goats, four sheep, and one human. One sample was a pig bone from the Neolithic Age, 20 were from the Bronze Age, including 15 pigs, four horses, and one sheep. The remaining 31 were from Liaojin Dynasties, including 19 pigs, four horses, three sheep, two cattle, two goats, and one human.

Collagen Preparation and Isotopic Measurements

The collagen extraction process primarily refers to the method adopted by Jay and Richards (2005). The surface of bones was cleaned, and 2–3 g samples were obtained. They were then put separately in a 50 ml beaker, and 30 ml of 0.5 M HCl solution was added and soaked at 4°C. The acid solution was replaced every 2 days. When the bone samples were soft with no obvious bubbles on the bone surfaces, the bone samples were washed to a neutral pH with deionised water. The neutral bone samples were then soaked in 0.125 M NaOH solution for 20 h. The samples were washed with deionised water until they had neutral pH levels. The neutral bone samples were soaked in a 0.001 M HCl solution at 70°C for 48 h and then filtered into a test tube while hot to obtain a

TABLE 1 | Isotopic results and sample information for fauna from the Changshan site.

Lab ID.	Context	Species	Period	Element	C (%)	N (%)	C/ N	δ^{13}C (‰)	δ^{15} N (‰)
L1	16LCIH004①:1	Pig (Sus)	Liaojin Dynasties	Humerus	22.9	15	1.8	−19.9	4.9
L2	16LCIH004①:2	Pig (Sus)	Liaojin Dynasties	Humerus	42.3	12.9	3.8	−19.3	4.6
L3	16LCIH004①:3	Pig (Sus)	Liaojin Dynasties	Humerus	42.8	14.4	3.5	−20	5.5
L4	16LCIH004①:7	Pig (Sus)	Liaojin Dynasties	Radius	39.1	14	3.3	−20.4	4.3
L5	16LCIH004①:8	Sheep (Ovis)	Liaojin Dynasties	Radius	42.5	14.8	3.4	−20.8	6.3
L6	16LCIH004①:12	Pig (Sus)	Liaojin Dynasties	Femur	41.1	14.7	3.3	−19.4	5.4
L7	16LCIH004①:13	Pig (Sus)	Liaojin Dynasties	Tibia	43.6	14.7	3.5	−18.8	6.3
L8	16LCIH019:1	Pig (Sus)	Liaojin Dynasties	Humerus	43.1	14.6	3.5	−19.6	4.5
L9	16LCIH019:2	Pig (Sus)	Liaojin Dynasties	Humerus	—	—	—	—	—
L10	16LCIH019:3	Pig (Sus)	Liaojin Dynasties	Humerus	40.5	14.4	3.3	−19.7	4.3
L11	16LCIH019:13	Pig (Sus)	Liaojin Dynasties	Tibia	39.9	12.5	3.7	−20.2	6
L12	16LCIH025①:1	Pig (Sus)	Liaojin Dynasties	Tibia	41.1	14.8	3.3	−20.6	4.2
L13	16LCIH025①:3	Sheep (Ovis)	Liaojin Dynasties	Tibia	43.7	15.5	3.3	−17	5.3
L14	16LCIH069①:1	Pig (Sus)	Bronze Age	Radius	39.7	13.7	3.4	−20	3.9
L15	16LCIH069:1	Pig (Sus)	Bronze Age	Humerus	41.9	14.9	3.3	−19.6	4.5
L16	16LCIH069:2	Pig (Sus)	Bronze Age	Humerus	2.5	1.6	1.8	−21.8	—
L17	16LCIH069:3	Pig (Sus)	Bronze Age	Humerus	39.3	14.1	3.3	−19.8	4.4
L18	16LCIH069:11	Pig (Sus)	Bronze Age	Femur	—	—	—	—	—
L19	16LCIH069:12	Pig (Sus)	Bronze Age	Femur	34.6	13.1	3.1	−19.2	5.4
L20	16LCIH069:13	Pig (Sus)	Bronze Age	Femur	16.8	5.5	3.6	−19.2	5.7
L21	16LCIH069:14	Pig (Sus)	Bronze Age	Tibia	38.7	12.4	3.7	−18.9	6.1
L22	16LCIH069:15	Pig (Sus)	Bronze Age	Tibia	—	—	—	—	—
L23	16LCIH069:17	Pig (Sus)	Bronze Age	Tibia	34.7	12.7	3.2	−19.1	5.4
L24	16LCIH072:1	Pig (Sus)	Bronze Age	Humerus	41.8	13.3	3.7	−14	7.2
L25	16LCIH072①:1	Pig (Sus)	Bronze Age	Radius	41.1	15	3.2	−14.1	7
L26	16LCIH074①:1	Pig (Sus)	Liaojin Dynasties	Tibia	38.8	13.8	3.3	−19.4	5.1
L27	16LCIH078①:2	Pig (Sus)	Liaojin Dynasties	Tibia	44.9	14.4	3.6	−19.5	6.4
L28	16LCIH087①:1	Cattle (Bos)	Liaojin Dynasties	Tibia	41.5	14.7	3.3	−12.9	8.1
L29	16LCIG004④:3	Horse (Equus)	Liaojin Dynasties	Femur	40.2	15.2	3.1	−19.3	3.5
L30	16LCIG004⑤:2	Horse (Equus)	Liaojin Dynasties	Tibia	41.4	14.2	3.4	−20.3	3.8
L31	16LCIG005①:1	Pig (Sus)	Bronze Age	Humerus	39.5	14.5	3.2	−20.8	5.9
L32	16LCIG005②:3	Horse (Equus)	Bronze Age	Tibia	43.1	15.4	3.3	−16.5	5.2
L33	16LCIG006①:1	Pig (Sus)	Liaojin Dynasties	Tibia	42	14.7	3.3	−20.2	4.9
L34	16LCIG006③:8	Goat (Capra)	Liaojin Dynasties	Radius	40.4	14.3	3.3	−21.5	5.9
L35	16LCIG006③:9	Sheep (Ovis)	Liaojin Dynasties	Radius	41.1	14.5	3.3	−20.6	5.4
L36	16LCIG006③: 12	Pig (Sus)	Liaojin Dynasties	Tibia	43.4	15	3.4	−20.9	5.1
L37	16LCIG007①:2	Pig (Sus)	Liaojin Dynasties	Radius	40.1	14.6	3.2	−19.9	4.9
L38	16LCIG007①:3	Pig (Sus)	Liaojin Dynasties	Tibia	43.1	15	3.4	−18.9	5.6
L39	16LCIG007②:1	Horse (Equus)	Liaojin Dynasties	Tibia	42.2	15.8	3.1	−15.2	8
L40	16LCIG007③:1	Cattle (Bos)	Liaojin Dynasties	Humerus	42.8	14.9	3.4	−19.9	3.8
L41	16LCIG008②:3	Pig (Sus)	Liaojin Dynasties	Radius	42.5	14.6	3.4	−20.1	4.1
L42	16LCIG008②:4	Horse (Equus)	Liaojin Dynasties	Radius	41.8	14.7	3.3	−19	4.2
L43	16LCIT0305③:1	Pig (Sus)	Neolithic Age	Humerus	—	—	—	—	—
L44	16LCIT0604①:1	Pig (Sus)	Liaojin Dynasties	Tibia	40.8	14.3	3.3	−19.7	6.2
L45	16LCIT0902①:1	Goat (Capra)	Liaojin Dynasties	Radius	42.8	15.4	3.3	−19.1	6.4
L46	16LCIT1002②:1	Horse (Equus)	Bronze Age	Radius	40.7	14.5	3.3	−19.3	4.8
L47	16LCIT1002②:3	Pig (Sus)	Bronze Age	Femur	41	14.6	3.3	−20.4	6.5
L51	16LCIH007①:2	Human (Homo)	Liaojin Dynasties	Scapula	41.9	15.1	3.2	−13.9	10.3
L52	16LCIH069:10	Pig (Sus)	Bronze Age	Femur	—	—	—	—	—
L53	16LCIH053:1	Horse (Equus)	Bronze Age	Femur	36.1	12	3.5	−19.5	3.9
L54	16LCIH069:19	Sheep (Ovis)	Bronze Age	Tibia	35.9	11.5	3.6	−19.7	5
L55	16LCIH053:2	Horse (Equus)	Bronze Age	Talus	4.5	105.3	0.1	−20.3	4.9

Note: Bronze Age (c. 2000–256 BC); Liaojin Dynasties (907–1234 AD).

collagen solution, and then placed in a freeze dryer for 48 h to obtain collagen.

The determinations of the collagen carbon and nitrogen isotopes were completed in the stable isotope analysis laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences. An elemental analyser was combined with a gas isotope mass spectrometer EA-IRMS to complete the tests. The Delta V model of mass spectrometer was used. The organic carbon standards used for determining the C and N contents were graphite and urea, respectively, and the standard substance used for nitrogen was glycine. In the process of sample testing, one tin cup blank and one standard substance were added for every six sample test sequences. The standard substances used for the carbon isotope measurements were GBW04407 (δ^{13}C = −22.43%) and IVA urea

($\delta^{13}C$ = −49.1%), and the standard substances used for the nitrogen isotope measurements were USGS64 ($\delta^{15}N$ = 1.76%) and USGS65 ($\delta^{15}N$ = 20.68%). The measured sample values were corrected using a two-point calibration method. The carbon values were presented relative to the value of the international standard VPDB, and the nitrogen values were presented relative to that of the international standard Air-N_2 (**Table 1**).

RESULT

Results of Stable Isotope Testing

As shown in **Table 1**, L9, L18, L22, L43, and L52 failed in collagen extraction. Generally, the other bone collagen discussed below had an average carbon content of 38.4 ± 8.9%, with a range of 2.5–44.9%, an average nitrogen content of 15.7 ± 13.5%, with a range of 1.6–105.3%, and atomic C/N ratios in the range of 0.1–3.8, unlike those of modern bones (41.0% carbon content, 15.0% nitrogen content, and 2.9–3.6 C/N ratio) (DeNiro 1985; Ambrose 1990). This suggested that some samples could not be used for stable isotope analysis.

After careful consideration of the three standards, the atomic C/N ratios of L1, L2, L11, L16, L21, L24 and L55 were out of the range 2.9–3.6 (DeNiro 1985). Thus, these samples could not be studied further. Finally, the remaining samples (n = 40) retained their *in vivo* isotopic signatures.

Isotopic Results of Human and Animals

A scatter plot of the isotopic data from the human and animals is depicted in **Figure 3**. One human had high $\delta^{13}C$ value (−13.9%) and $\delta^{15}N$ value (10.3%), suggesting that the human consumed large quantity of C_3/C_4-based animal protein (Zhang et al., 2003; Pei et al., 2008; Hou et al., 2021). The $\delta^{13}C$ values for all the fauna (n = 39) ranged from −21.5% to −12.9%, with an average of −19.2 ± 1.8‰, while the $\delta^{15}N$ values ranged from 3.5 to 8.1‰, with an average of 5.3 ± 1.1%, reflecting a diet mainly composed of large quantities of C_3-based plants (Ambrose and Norr 1993; Hu 2002).

As shown in **Figure 3**, the $\delta^{13}C$ values of all pigs ranged from −20.9% to −14.1%. The average $\delta^{13}C$ value (−19.6 ± 1.3%, n = 24) suggested that they predominately consumed C_3-based diets (Hu et al., 2009). However, the wide variation of the $\delta^{13}C$ values suggested that these pigs had diverse diets, with some consuming substantial C_4-based diets (Hu et al., 2006; Guo et al., 2011), that is, one pig (L25: −14.1%, 7.0%) in the Bronze Age, also consumed a large quantity of C_4-based food. The pig $\delta^{15}N$ values ranged from 3.9 to 7.0% with an average of 5.2 ± 0.9% (n = 24), suggesting that pigs mostly consumed plants. Sheep (range −20.8‰ to −17.0% and range 5.0–6.3%, means −19.5 ± 1.8% and 5.5 ± 0.6%, respectively, n = 4), goats (L34: −21.5%, 5.9%; L45: −19.1%, 6.4‰; n = 2), and horses (range −20.3% to −15.2% and range 3.5–8.0%, means −18.4 ± 1.9% and 4.8 ± 1.5%, respectively, n = 4) also show isotopic patterns similar to pigs, reflecting a similar diet.

Notably, two cattle (L34: −12.9%, 8.1%; L45: −19.9%, 3.8%; n = 2) have a different isotopic pattern. As shown in **Figure 3**, L45 had a diet similar to most of the above animals. However, L34's diet might have been mainly composed of a large

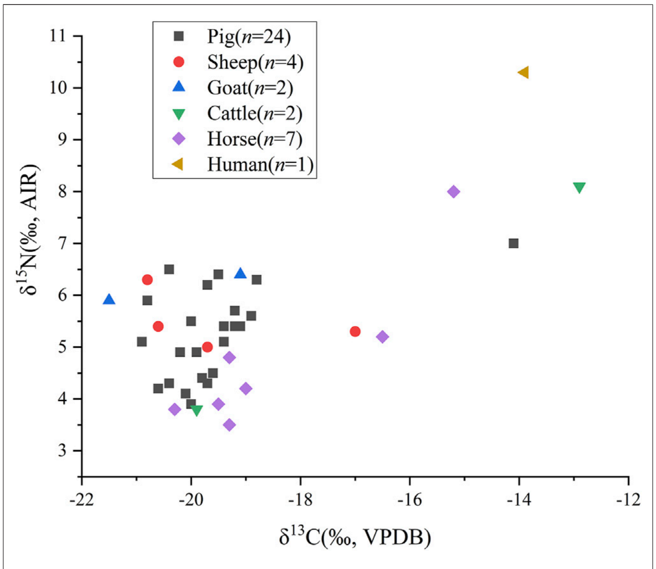

FIGURE 3 | Scatter plot of the stable isotopes of animal bones from the Changshan site.

quantity of C_4-based food, such as C_4-based fodder (Makarewicz 2017).

DISCUSSION

Diet of Animals in the Bronze Age

The $\delta^{13}C$ and $\delta^{15}N$ values scatter plots of animal bone collagen in the Bronze Age are shown in **Figure 4**. The carbon and nitrogen values of all the data are concentrated (pigs: −19.1 ± 1.9%, 5.4 ± 1.0%, n = 9; horses: −18.5 ± 1.4%, 4.7 ± 0.5%, n = 3; sheep: −19.7%, 5.0%, n = 1), and the nitrogen values fall within the trophic level of herbivores (Ambrose and Norr 1993). Overall, sheep, horses, and pigs predominately relied on a diet of C_3 plants, probably from plant leaves and C_3-typed grasses. Meanwhile, one horse (L32: −16.5%, 5.2%) had high $\delta^{13}C$ values, reflecting a C_3/C_4-based diet with a small amount of C_4-based fodder. In addition, one pig (L25: −14.1%, 7.0%) had higher $\delta^{13}C$ and $\delta^{15}N$ values among these animals, indicating that the pig may have consumed C_4-based fodder, including millet and/or millet by-products.

Since the Holocene, the vegetation in northern China has been dominated by C_3 plants with low $\delta^{13}C$ average values (−26.5%) (O' Leary 1981; Ambrose 1991; Guan et al., 2007). Millets comprised a vast majority of C_4 plants belonging to the C_4 category with a high $\delta^{13}C$ average (−12.5‰), which were cultivated during the Neolithic period in northern China (Dong et al., 2016). The $\delta^{13}C$ values of the heavy millet consumers are mostly high in northern China, with a value of ≥−12‰ (Barton et al., 2009). At the Changshan site, the ubiquity of foxtail millet (*Setaria italica*, n = 25) and common millet (*Panicum miliaceum*, n = 33) are 15% and 12%, respectively (Chen 2019), indicating that millet-based agriculture was not an important subsistence strategy for populations residing in the East Liao River Basin in the Bronze Age.

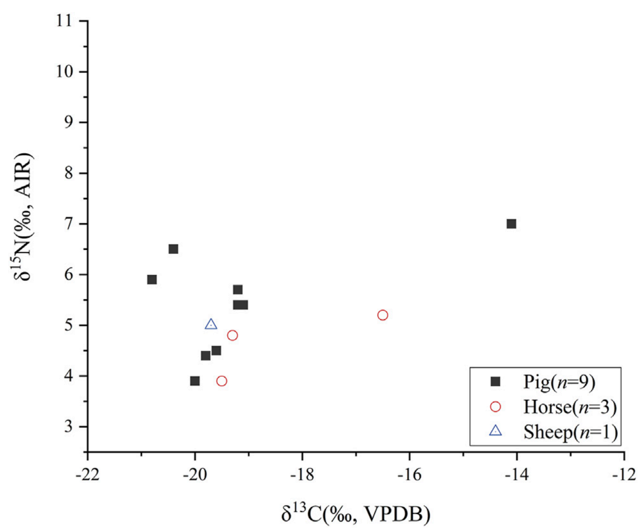

FIGURE 4 | Scatter plot of the stable isotopes of animal bones from the Changshan site during the Bronze Age.

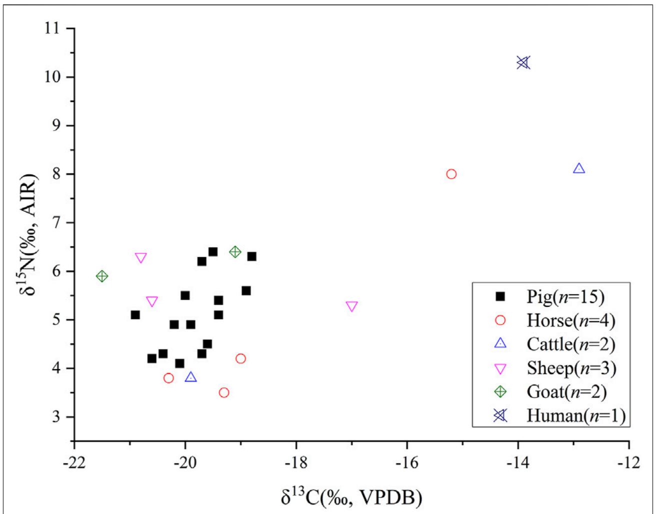

FIGURE 5 | Scatter plot of the stable isotopes of animal bones from the Changshan site during the Liaojin Dynasties.

Thus, the diet of above animals shows that livestock management strategies are dominated by a free-range economy based on wild plants, with C_4-based fodder representing a minor proportion of feeding strategy in East Liao River Basin during the Bronze Age.

Diet of Human and Animals in the Liaojin Dynasties

The scatter plots of $\delta^{13}C$ and $\delta^{15}N$ values of animal bone collagen from the Liaojin Dynasties are shown in **Figure 5**. The carbon and nitrogen values of pigs (−19.8 ± 0.6%, 5.1 ± 0.7%, *n* = 15), sheep (−20.7 ± 0.1%, 5.9 ± 0.5%, *n* = 2), goats (−20.3 ± 1.2%, 6.2 ± 0.3%, *n* = 2), one cattle (L40: −19.9%, 3.8%), and most horses (−19.5 ± 0.6%, 3.8 ± 0.3%, *n* = 3) showed that these animals predominately relied on a diet of C_3 plants. Herbivores such as sheep, horses, and goats have low $\delta^{13}C$ and $\delta^{15}N$ values, forming an isotopic baseline for understanding the wild ecosystem, which were likely dominated by C_3 plants and C_3 grasses (e.g., Guan et al., 2008).

One sheep (L13: −17.5%, 3.0%), and one horse (L39: −15.2%, 8.0%) had a slightly high $\delta^{13}C$ values, which might relate to more C_4 food, including C_4-based fodder, in their diet. The cattle of L28 had the highest $\delta^{13}C$ value (−12.9%) and high $\delta^{15}N$ value (8.1%), indicating that the cattle with a different feeding strategy consumed a large amount of C_4-based fodder, such as millets and millet by-products (Makarewicz 2017).

The high $\delta^{13}C$ value (−13.9‰) and $\delta^{15}N$ value (10.3‰) in human bone collagen suggested that the individual consumed a large amount of C_4-based animal protein. The $\delta^{13}C$ value was also positively related to the mean value for most animals (−20.0 ± 1.3%, *n* = 25; excluding the cattle of L28: −12.9%, 8.1%). This was probably because this person also consumed animal protein with high $\delta^{13}C$ values.

Although millet agriculture developed in the East Liao River Basin during the Liaojin Dynasties, it just only used as an auxiliary subsistence strategy. For example, at the Changshan site, the ubiquity of foxtail millet (*n* = 123) and common millet (*n* = 177) are 22% and 25%, respectively during this period (Chen 2019). C_4-based food, such as millet, meat, and egg, might have been the commodity provided to populations by the Central Plains in the Liaojin dynasties, as described in the Chapter of Shi Huo Zhi—Liao Shi 辽史-货志 and Shi Huo Zhi—Song Shi 宋史-食货志 (Cui et al., 2021). According to the book, millet was transported to the capital of Liao, Chifeng, which was close to the current Changshan site (Liang and Bao 2008). Meanwhile, some immigrants from the agricultural area might have lived in this area for a short period (Liang and Bao 2008), as described in the Chapter of Shi Huo Zhi—Jin Shi 金史-食货志. However, as more human bones are currently unavailable at the Changshan site, we cannot reconstruct human diet and subsistence.

Based on the diet of above animals, we can conclude that livestock management strategies used at that period were like those used in the Bronze Age.

Undiversified Pig Management Strategy Over a Long Term

Generally, a similar diet was present for animals, especially the pigs, in the Changshan site over a long period, indicating that a similar management strategy for animals existed in this region.

Notably, the number of animals of each species ($n \leq 3$) was small, especially domesticated animals, such as sheep, goats, cattle, and horses, during both the Bronze Age and the Liaojin Dynasties. Thus, we would not be able to further discuss the relationship between animal dietary patterns and the management strategy over a long period. However, the number of pigs during both periods (the Bronze Age, *n* = 9; the Liaojin Dynasties, *n* = 15) is sufficient for discussing the pig management strategy in this region. Meanwhile, to gain a better understanding of pig management strategies at the Changshan site, the published isotopic data from near this area and

TABLE 2 | Summary of isotopic results for Pigs from the previous published data in different region, China.

Region	Site	Period	*n*	δ^{13}C ± SD (‰)	δ^{15} N ± SD (‰)	Reference
Dongliao River	Changshan	Bronze Age	9	−19.1 ± 2.0	5.4 ± 1.0	This study
		Liaojin Dynasties	15	−19.8 ± 0.6	5.1 ± 0.7	
	Wanfa Bozi	Bronze Age	21	−21.3 ± 0.7	4.4 ± 0.5	Guan et al. (2007)
		Weijin Dynasties	5	−20.8 ± 0.3	4.7 ± 0.5	
Xiliao River	Xinglonggou	Bronze Age	8	−10.1 ± 4.4	7.5 ± 1.7	Zhang et al. (2017)
Central Plains	Xinzhai	Bronze Age	11	−8.5 ± 1.1	6.2 ± 0.9	Zhang et al. (2015)
	Erlitou	Bronze Age	22	−10.4 ± 2.7	7.3 ± 1.2	Wu et al. (2007)
	Taosi	Bronze Age	17	−6.8 ± 1.3	7.5 ± 0.6	Chen et al. (2012)
	Zhangdeng	Bronze Age	18	−7.5 ± 1	7.6 ± 0.5	Hou et al. (2013)

Note: Bronze Age (c. 2000–256 BC); Weijin Dynasties (220–420 AD); Liaojin Dynasties (907–1234 AD).

the Central Plains, dating from the Bronze Age (c. 2000–256 BC) to the Liaojin Dynasties 907–1234 AD), is summarized in **Table 2**, and is showed in **Figure 6**.

As shown in **Figure 6**, there was no shift in the δ^{13}C and δ^{15}N values of pigs from the Bronze Age (−19.1 ± 2.0%, 5.4 ± 1.0%, n = 9) to the Liaojin Dynasties (−19.8 ± 0.6%, 5.1 ± 0.7%, n = 15), indicating that they had a similar diet with predominantly C_3 plants and might have been fed by a similar free-range strategy. Furthermore, the independent *t*-test statistical analysis of the difference of mean δ^{13}C and δ^{15}N values showed non-significant (δ^{13}C: p = 0.225; δ^{15}N: p = 0.434, respectively) results. Additionally, the pigs in the Wanfa Bozi site (**Figure 1**), which was located close to the Changshan site dating back to the Bronze Age and the Weijin Dynasties (220–420 AD), presented an isotopic pattern (Guan et al., 2007) similar to that of the Changshan site (**Table 2** and **Figure 6**). This confirmed that there was no change in the pig management strategy in the East Liao River Basin over a long period. As mentioned in the Introduction section, pig management strategies in southern China also adopted a free-range style (Dong and Yuan 2020), similar to that of the Changshan site.

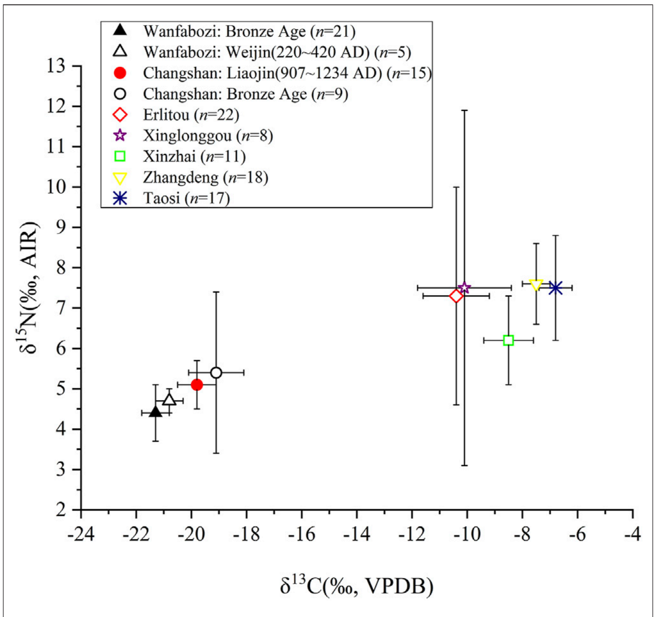

FIGURE 6 | Error bar chart for this study and previous published data in different region, China.

However, the pig with a different isotopic pattern (**Table 2** and **Figure 6**) was presented in the West Liao River Basin and the Central Plains in the Bronze Age (**Figure 1**). Both areas were dominated by millet agriculture (Dong et al., 2016), and pigs mainly consumed millet-based food, showing high δ^{13}C values. As demonstrated in **Table 2** and **Figure 6**, pigs in the Central Plains, such as the Taosi (Chen et al., 2012), Erlitou (Wu et al., 2007), Zhangdeng (Hou et al., 2013), and Xinzhai sites (Wu et al., 2007; Zhang and Zhao, 2015; Dai et al., 2016), as well as in the West Liao River Basin (Liu et al., 2012), such as Xinglonggou site (Zhang et al., 2017), had higher δ^{13}C and δ^{15}N values than those of the pigs in the East Liao River Basin, such as the Changshan and Wanfa Bozi sites. This indicated that such pigs predominately relied on a diet of millet-based food. Since the spread of millet agriculture into the middle reaches of Yangtze River (Dong et al., 2016; Hu 2021), the diet of pigs (δ^{13}C: −13.4 ± 3.2%, δ^{15}N: 7.1 ± 1.2%, respectively, n = 28) at the Qinglongquan site (c. 3000–c. 2200 BC) reflected millet-based food to some extent (Guo et al., 2011; Chen et al., 2015).

Thus, what is the reason for using different pig management strategies in different areas? In the East Liao River Basin from the Bronze Age to the Liaojin Dynasties, the past populations in Changshan area made their living in a stable climate with warm and moist grasslands and/or forests and with abundant natural resources, such as plants, wild animals, and fishes, which were adequate sources of food to them (Chen 2007). Similar conditions also existed in southern China over a long period (e.g., Dong and Yuan 2020; Hongo et al., 2021). Although pigs provided meat resources, the driving force for intensive pig feeding was weak in these areas, leading to the existence of free-range pigs. On the contrary, multiple lines of evidence have revealed that millet-based agriculture became a dominant subsistence economy in the West Liao River Basin, the Central Plains, and the middle reaches of Yangtze River in the Neolithic Periods (Dong et al., 2016). Thus, the past populations used pigs for meat resources, and pigs were fed based on the millet-based agriculture (Hou 2019).

Finally, the East Liao River Basin had a stable climate and abundant natural resources, leading to a steady subsistence pattern over a long period, with pigs being freely fed based on the wild ecosystem.

CONCLUSION

Based on the stable isotope analysis of human and animal bones from the Changshan site, the following conclusions can be drawn:

1) Most animals had a diet composed of C_3 plants. A free-range management strategy was used based on the wild ecosystem of the Changshan site. However, human and a few animals consumed a certain amount of C_4 food, such as millet-based food.
2) No dietary shift was observed for most animals, especially pigs from the Bronze Age to the Liaojin Dynasties, indicating an undiversified pig management strategy in the East Liao River Basin.
3) The East Liao River Basin had a stable climate and abundant natural resources, leading to a similar pig management strategy over a long period.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

LH, XL, LB and CW designed the study. LH, XL, YG, CW and HL conducted the study. LH, XL, LB and CW wrote an initial version of the manuscript. All co-authors reviewed and made modifications to the final version of the manuscript.

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