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RESEARCH ARTICLE

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# Breastfeeding, weaning, and dietary practices during the Western Zhou Dynasty (1122–771 BC) at Boyangcheng, Anhui Province, China

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## Abstract

**Objectives:** Here we investigate breastfeeding and weaning practices and adult dietary habits at the Western Zhou Dynasty (1122–771 BC) site of Boyangcheng (薄阳城) located in Anhui Province, China. In addition, we utilize the differences in bone collagen turnover rates between rib and long bones from the same individual to examine past life histories, such as changes in diet or residence.

**Materials and methods:** Bone collagen from both the rib and long bones (either femora or humeri) of 42 individuals was measured for stable isotope ratios of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$). In addition, $\delta^{13}C$ and $\delta^{15}N$ values are reported for 35 animals (dogs, cows, horses, pigs, and deer).

**Results:** The human $\delta^{13}C$ values range from −20.7‰ to −12.0‰ with a mean value of −18.8 ± 1.6‰. The human $\delta^{15}N$ values range from 9.1‰ to 13.4‰ with a mean value of 10.9 ± 1.0‰. The animals display a wide range of $\delta^{13}C$ (−21.5‰ to −8.2‰; −15.8 ± 4.5‰) and $\delta^{15}N$ values (4.0‰ to 9.5‰; 6.5 ± 1.8‰).

**Conclusions:** The adult $\delta^{13}C$ and $\delta^{15}N$ results indicate that mixed $C_3$ (rice) and $C_4$ (millet) terrestrial diets with varying levels of animal protein (mostly pigs and deer) were consumed. The elevated subadult $\delta^{15}N$ results return to adult levels by approximately 3–4 years of age, indicating that the weaning process was completed during this period. Individuals between 2 and 10 years old, with lower $\delta^{13}C$ and $\delta^{15}N$ results than the adult mean, possibly consumed more plant-based diets, and this is consistent with Chinese medical teachings ~1500 years later during the Tang Dynasty (AD 618–907). The isotopic offsets between the ribs and long bones revealed that five adults experienced dramatic dietary shifts in their later lives, switching from predominately $C_3/C_4$ to $C_3$ diets. This research provides the first isotopic information about ancient Chinese breastfeeding and weaning practices and establishes a foundation for future studies to examine diachronic trends.

KEYWORDS
bone collagen turnover, Bronze Age, China, millet, migration, paleodiet, rice

  

## 1 | INTRODUCTION

Investigating the breastfeeding and weaning habits of infants and children in past societies can aid in the understanding of how nutrition influences childhood health and survivorship, as human breastmilk contains various nutrients designed for optimal infant growth and many factors necessary for ideal immunological development (Cunningham, 1995; Popkin, Lasky, Litvin, Spicer, & Yamamoto, 1986). In particular, the weaning process is a critical and potentially dangerous period of development related to infant morbidity and mortality in that the introduction of complementary foods can expose infants and young children to pathogens and nutritional stress (Katzenberg, Herring, & Saunders, 1996; Knodel and Kintner, 1977). Infant and child feeding practices are also culturally unique and specifically determined, and thus can be examined to detect motivations behind feeding practices in certain populations (Dettwyler and Fishman, 1992; Sellen and Smay, 2001; Wright and Yoder, 2003). Therefore, the breastfeeding practices and weaning foods given to young children are important for the health and fitness of a population.

While infants and children are not frequently recovered in large numbers at Chinese archaeological sites, they are sometimes found associated with special burial customs such as urn burials (remains of infants and young children are placed in urns and buried in residential areas) (Xu, 1989). In the past, there has been little research concentrated on the bioarcheology of infants and children in China (Chen and Zhou, 2013; Gong, 2006), as most studies focused on child burial goods and customs. In addition, there is little historical or archaeological evidence about breastfeeding, weaning or childhood diets in ancient China. It is not until the Tang Dynasty (AD 618–907) that the first detailed and authoritative document about childhood diet and infant feeding practices was written by the famous physician Simiao Sun (孙思邈) (AD 581–682) in the medical book *Qianjinfang* (千金方) (Sun, 1993).

An area of research that has received increased attention in archaeology is the isotopic investigation of breastfeeding and weaning practices and childhood and adolescence diets (Bourbou, Fuller, Garvie-Lok, & Richards, 2013; Choy, Jeon, Fuller, & Richards, 2010; Dupras and Tocheri, 2007; Fuller, Molleson, Harris, Gilmour, & Hedges, 2006a; Richards, Mays, & Fuller, 2002; Schurr, 1998; Tsutaya, Ishida, & Yoneda, 2015). However, there have been no isotopic applications that have examined these topics in China. Here we investigate breastfeeding and weaning patterns as well as adult dietary habits at the Western Zhou Dynasty (1122–771 BC) site of Boyangcheng (薄阳城) located in Anhui Province, China (Figure 1a,b). In addition, we utilize the differences in bone turnover between rib and long bones (femora or humeri) from the same individual to reconstruct past life histories, especially to explore dietary or residence changes, as ribs represent a later life dietary signal (perhaps 2–5 years before death in adults), whereas femora show a longer term (perhaps +10 years in adults) average due to different bone turnover rates (Cox and Sealy, 1997; Hedges, Clement, Thomas, & O'Connell, 2007; Parfitt, 2002). This work provides the first results about ancient Chinese breastfeeding and weaning patterns and sets the stage for future studies.

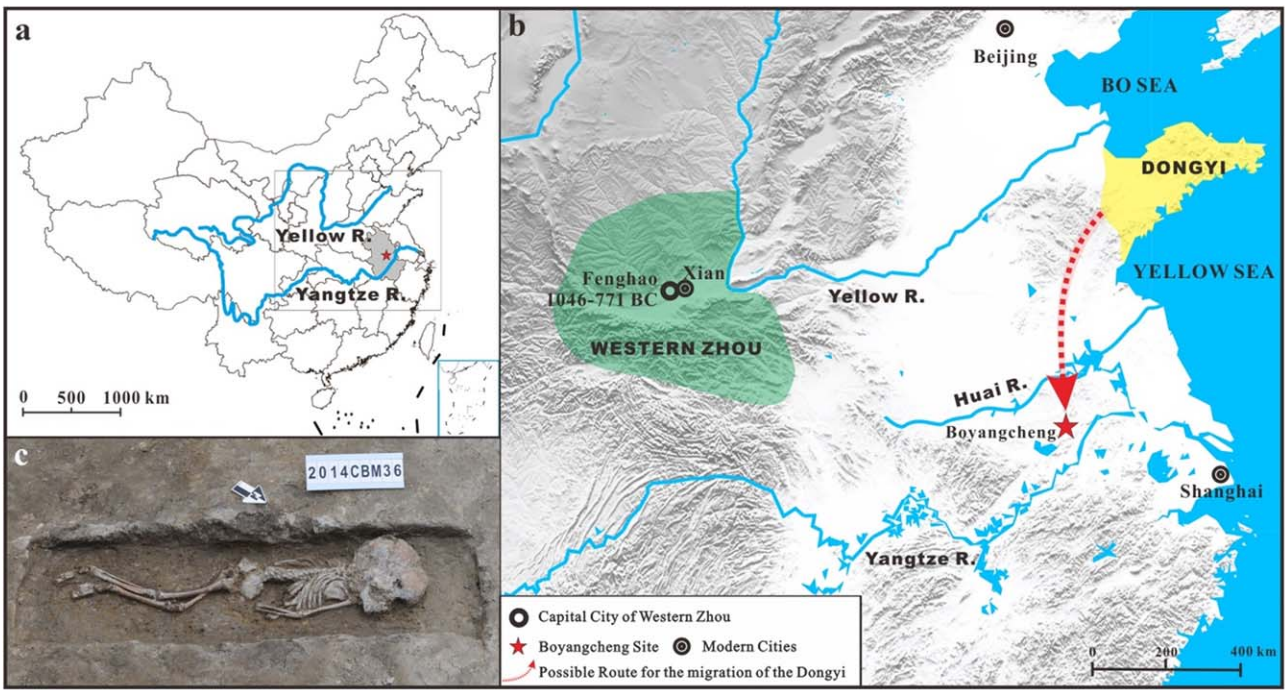


**FIGURE 1** (a) Map showing the location of the Boyangcheng site in Anhui Province (shaded), China. (b) Map showing the central region of the Western Zhou (shaded green). Yellow represents the Shandong peninsula where the Dongyi people lived before and during the Western Zhou Dynasty. Boyangcheng is located in the Jianghuai region (the area between the Huai and Yangtze Rivers). (c) Photo of M36 (~6-year-old child) during the Boyangcheng excavation

### 1.1 | Reconstruction of breastfeeding/weaning practices with stable isotope ratios

Nitrogen stable isotope ratios ($\delta^{15}N$) are used to investigate breastfeeding and weaning patterns in modern and archaeological populations (for an excellent comprehensive review, see Tsutaya and Yoneda, 2015), as there is $^{15}N$-enrichment of ~2‰–3‰ between breastmilk and infant tissues (Fogel, Tuross, & Owsley, 1989; Fuller, Fuller, Harris, & Hedges, 2006b). With the onset of the weaning process, the $\delta^{15}N$ values of an infant or young will decrease as a result of the consumption of $^{15}N$-depleted complementary foods. Once a child is fully weaned, or at the cessation of breastfeeding, their $\delta^{15}N$ values are nearly equivalent to their mother, assuming that the mother and child consumed similar diets. Carbon stable isotope ratios ($\delta^{13}C$), can also be used to detect breastfeeding and weaning practices, as $^{13}C$-enrichment of ~1‰ is observed between a mother and an exclusively breastfed infant (Fuller et al., 2006b). During the weaning process, infant $\delta^{13}C$ values have been observed to decline more rapidly than $\delta^{15}N$ values to maternal levels, evidence that $\delta^{13}C$ values can be used to track the timing of the onset of weaning. Therefore, by measuring the $\delta^{13}C$ and $\delta^{15}N$ values of infants and children at various ages, the introduction of weaning foods and the duration of breastmilk consumption can be reconstructed. However, it is important to note that the isotopic ratios can only be used as indicators of weaning age, rather than as an absolute measurement, since those who died in childhood may not fully represent those who survived to older age (Richards et al., 2002).

### 1.2 | Archaeological and historical background

Boyangcheng is regarded as a typical site of the Jianghuai (江淮) region and likely dates to the Western Zhou Dynasty (Figure 1a,b). The site is located in Chuzhou City, Anhui Province, China, and was discovered during the third national cultural relics survey in 2013. Unfortunately, the central area of the site was destroyed when the Chuzhou high-speed rail station was constructed before discovery, leaving only two corners, the northeast and northwest, with a total of 1500 $m^2$ excavated. During the rescue excavations, 42 human skeletons were recovered and 35 animal bones (dog, cow, horse, pig, and deer) (Figure 1c). Although no grave goods were found associated with these burials, the typological features of the artifacts (pottery, stone, and bronze tools discovered from the same stratum in the vicinity of the graves) indicate that the site is consistent in association to the Western Zhou Dynasty.

The Jianghuai region of Anhui Province is the area between the Yangtze River and Huai River (Figure 1b). As a result of its location in central China, it has been consistently considered as a transitional zone where the northern and southern cultures of China overlapped and mixed to form complex and unique cultural characteristics, especially during the Bronze Age when the ancient Chinese civilization developed toward unification (Gong, 1999; Tang, 2011). At Boyangcheng diverse cultural artifacts were recovered, and these objects constitute a complex and unique archaeological mosaic. Through artifact analysis (stone tools, pottery, and bronzes) and comparison with the surrounding sites of the region, the population at Boyangcheng is currently proposed to be influenced by the immigration events of the Dongyi (东夷) people who moved south from the Shandong area (Figure 1b) in the north of China.

According to ancient Chinese historical documents such as *Shiji* (史记) (Si, 1959), *Shangshu* (尚书) (Anonymous, 1986), and *Houhanshu* (后汉书) (Fan, 1965), the Dongyi people lived on the modern day Shandong peninsula during the pre-Zhou era. They owned fertile land, exploited fish and clams, produced silk, had a powerful military, and were believed to have developed agriculture and animal husbandry. Throughout the Western Zhou Dynasty, the rulers of Zhou launched several wars against the Dongyi people of the Shandong region, forcing them to migrate to the Jianghuai area (Loewe and Shaughnessy, 1999). This influx of migrants contributed to the formation and development of the unique Jianghuai civilization which shows characteristics of both north and south China (He, 1986; Li, 1991; Yan, 1989). In addition to these historical accounts, evidence that the Dongyi migrated to the Jianghuai region is found in their pottery. A type of sandy brown pottery without decorations, which is associated with the culture of the Dongyi people, was introduced to the Jianghuai region during the Zhou Dynasty (Li, 2007; Wang, 1994; Xu, 2007). Further, inscriptions on the contemporary bronzes (site locations) also verify the wars between the Zhou and Dongyi throughout the Western Zhou Dynasty (Yan, 2009).

## 2 | MATERIALS AND METHODS

Individuals ($n = 42$) consisting of infants, children and adults and ranging in age from 2 to over 45 years old were examined and classified by a team of physical anthropologists led by Jinglei Zhang from the History Department at Nanjing University (Table S2). Age estimation and sex determination for each individual (where possible) were determined by standard methods (Ubelaker, 1999; White and Folkens, 2000; Zhu, 2005). Specifically, sex was determined by pelvic sexual dimorphism and age was estimated by morphological changes of the pubic symphysis. Individuals under the age of 14 were defined as subadults, those between 14 and 18 years of age were classified as teenagers, and individuals over 18 years of age were defined as adults (Zhu, 2005). Rib samples were selected from each individual ($n = 37$) if they were available and where possible femora or humeri ($n = 42$) were also sampled, so that a total of 79 specimens were prepared for collagen extraction and isotopic analysis. In addition, faunal remains (dog, pig, cow, horse, and deer; $n = 35$) were extracted for collagen and isotopically analyzed to establish a baseline for interpretation of the human diets.

All bones were prepared for collagen extraction at the Key Laboratory of Vertebrate Evolution and Human Origins of the Chinese Academy of Sciences, Institute of Vertebrate Palaeontology and Palaeoanthropology, Chinese Academy of Sciences, Beijing following the modified procedures detailed in Richards and Hedges, (1999). Briefly, ~0.5 g of bone was cleaned by sonication and then demineralized in a 0.5 M HCl solution at 4°C for 2 weeks, with the acid changed every 2 days. Samples were then gelatinized at 70°C in a pH = 3 solution for 48 hr. After purification with a 5 μm EZEE© filter, the solution was frozen and freeze dried for 2 days. The purified gelatin was measured at the

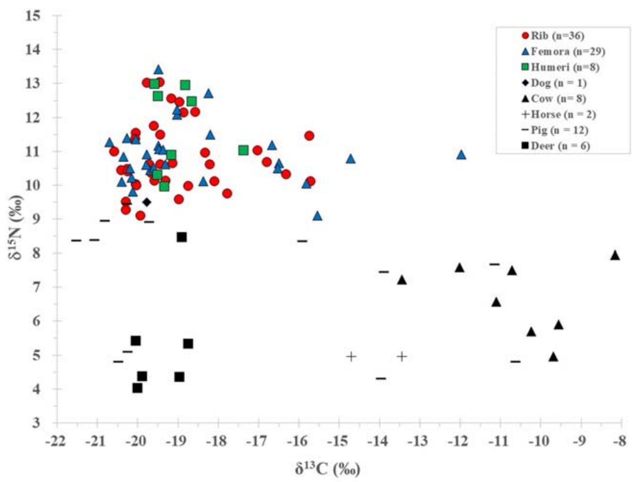


**FIGURE 2** All $\delta^{13}C$ and $\delta^{15}N$ results from the Western Zhou Dynasty (1122–771 BC) site of Boyangcheng, Anhui Province, China

Archaeological Stable Isotope Laboratory, Department of Archaeology and Anthropology, University of Chinese Academy of Sciences in Beijing. Approximately 0.5 mg of extracted gelatin was weighed in duplicate for carbon and nitrogen analysis, and the mass spectrometer used was an IsoPrime-100 IRMS coupled with Elementar Pyro Cube elemental analyzer. The stable isotope ratio results were analyzed as the ratio of the heavier isotope to the lighter isotope ($^{13}C/^{12}C$ or $^{15}N/^{14}N$) and reported as δ in parts per 1000 or "per mil (‰) relative to the internationally defined standards for carbon (Vienna Pee Dee Belemnite, VPDB) and nitrogen (Ambient Inhalable Reservoir, AIR). The standards were Sulfanilamide, IAEA-600, IEAE-N-1, IAEA-N-2, IAEA-CH-6, USGS-24, USGS 40, and USGS 41 and for every 10 samples, a collagen lab standard ($\delta^{13}C$ value of 14.7 ± 0.2‰ and $\delta^{15}N$ value of 6.9 ± 0.2‰) was also inserted in the run for isotopic calibration. The measurement errors were <0.2‰ for both $\delta^{13}C$ and $\delta^{15}N$ values.

## 3 | RESULTS

All isotopic results for the animals and humans are listed in Supporting Information, Tables S1 and S2 and plotted in Figure 2. In general, most bone samples produced good-quality collagen with elemental C:N between 2.9 and 3.6 (DeNiro, 1985), except for six animals and six humans with values outside of this range, and these were excluded from further discussion.

### 3.1 | Animals

The animals display a wide range of $\delta^{13}C$ (−21.5‰ to −8.2‰; −15.8 ± 4.5‰) and $\delta^{15}N$ values (4.0‰ to 9.5‰; 6.5 ± 1.8‰) (Figure 2). The single dog has $\delta^{13}C$ (−19.8‰) and $\delta^{15}N$ (9.5‰) results similar to the humans reflecting that it was likely consuming human refuse. The cattle ($n$ = 8) and horses ($n$ = 2) have elevated $\delta^{13}C$ results that indicate they consumed high amounts of $C_4$ plants, likely millet (Barton et al., 2009; Pechenkina, Ambrose, Ma, & Benfer, 2005; Wang et al., 2017). The pigs ($n$ = 12) display the most variable $\delta^{13}C$ (−21.5‰ to −10.6‰) and $\delta^{15}N$ (4.3‰–9.4‰) results which indicate a range of terrestrial $C_3$ and $C_4$ dietary consumption. In addition, a number of pigs have high $\delta^{15}N$ values (≥8‰) that likely reflect that they were fed human refuse or waste (Barton et al., 2009; Dai et al., 2016). The deer ($n$ = 6) have mean $\delta^{13}C$ (−19.4 ± 0.6‰) and $\delta^{15}N$ (5.3 ± 1.6‰) results that represent a terrestrial $C_3$ feeding behavior for a wild herbivore. However, the elevated $\delta^{15}N$ results of a single deer (BYC 29) might indicate that it was intentionally fed with some $^{15}N$-elevated plants by humans, possibly for hunting purposes (Dai et al., 2016) (Figure 2). In addition, the wide range of isotopic values for the domesticated animals, especially those that show evidence of $C_4$ consumption might indicate that they were being imported from distant locations to the Jianghuai region as only evidence of rice agriculture has been so far found at the site (see below).

### 3.2 | Humans

The $\delta^{13}C$ values of the entire human population have a large range from −20.7‰ to −12.0‰ with a mean value of −18.8 ± 1.6‰ (Figure 2). The majority of individuals have $\delta^{13}C$ results lower than −18‰, indicative of a predominately $C_3$ diet. However, the wide variety of $\delta^{13}C$ values suggests that the Boyangcheng population had heterogeneous diets that included inputs from $C_3$ and $C_4$ sources. The $\delta^{15}N$ results range from 9.1‰ to 13.4‰ with a mean value of

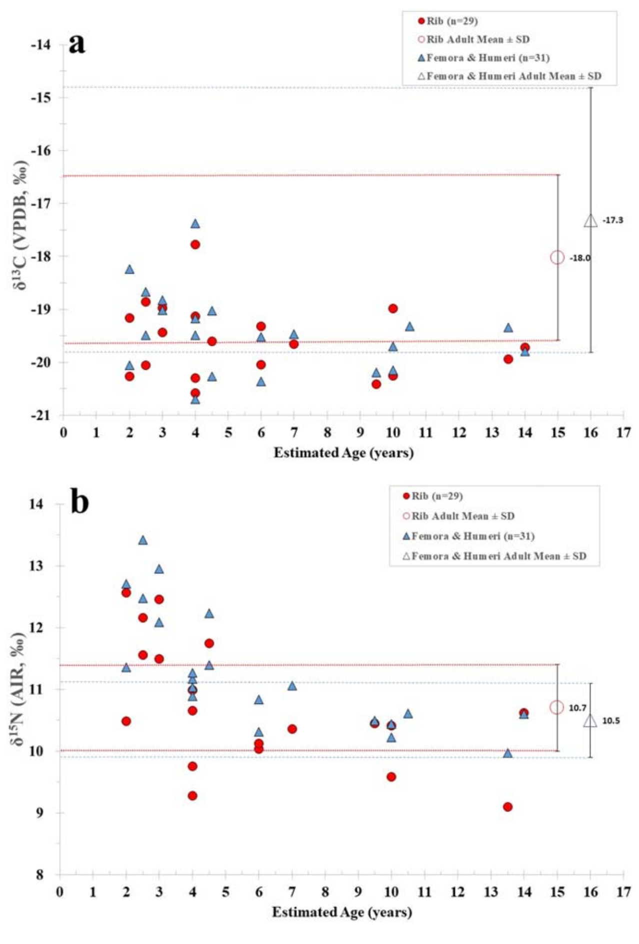


**FIGURE 3** Plot of (a) $\delta^{13}C$ and (b) $\delta^{15}N$ versus estimated age at death for individuals between 2 and 14 years old

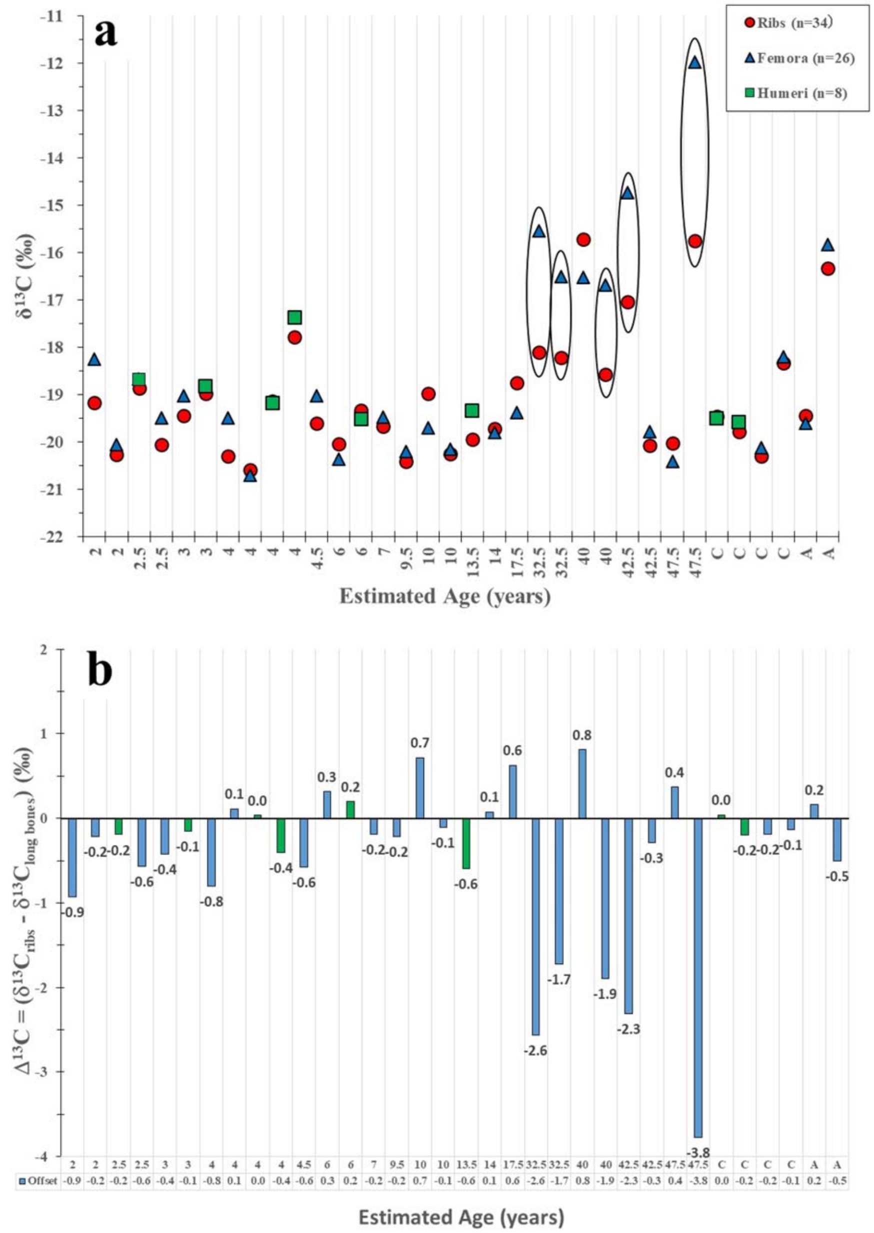


**FIGURE 4** (a) Plot of individual $\delta^{13}$C rib and long bone values versus estimated age at death for all individuals from the Boyangcheng site, Anhui Province, China. (b) Calculated $\delta^{13}$C offsets between ribs and femora/humeri ($\Delta^{13}C = \delta^{13}C_{ribs} - \delta^{13}C_{long\ bones}$) versus estimated age at death for all individuals (blue = femora; green = humeri). Note: C = child of unknown age; A = adult of unknown age

10.9 ± 1.0‰. The relatively large range of $\delta^{15}$N values is because the subadults have elevated $\delta^{15}$N values due to the breastfeeding effect (Fogel et al., 1989; Fuller et al., 2006b). The teenagers and adults greater than 14 years of age show a mean $\delta^{13}$C value of −17.6 ± 2.0‰, which indicates a mixed $C_3$/$C_4$ diet and have a mean $\delta^{15}$N value of 10.6 ± 0.6‰ which is evidence of a diet with contributions from both animal (e.g., pigs, cattle, and deer) and plant (including both rice and millet) protein.

## 3.3 | Subadults

The $\delta^{13}$C and $\delta^{15}$N results of the subadults (infants, young children, and adolescents below the age 14 years) are plotted with respect to the estimated age at death in Figure 3a,b to examine the relationships between the isotopic values and age. The adult mean isotopic values are also plotted for the ribs and long bones (femora or humeri). The $\delta^{13}$C values are not elevated above the standard deviations of the adult ribs and long bones (Figure 3a), but this is due to the large range of $\delta^{13}$C values that reflect mixed $C_3$/$C_4$ feeding in this population. Thus, this makes it impossible to determine when solid foods were introduced to an infant's diet at Boyangcheng. However, a number of individuals between 2 and 10 years old have $\delta^{13}$C values that are lower than the standard deviations of the adults, and this suggests a different weaning diet of a more $C_3$ terrestrial origin, with possibly less animal protein fed to the children (see below).

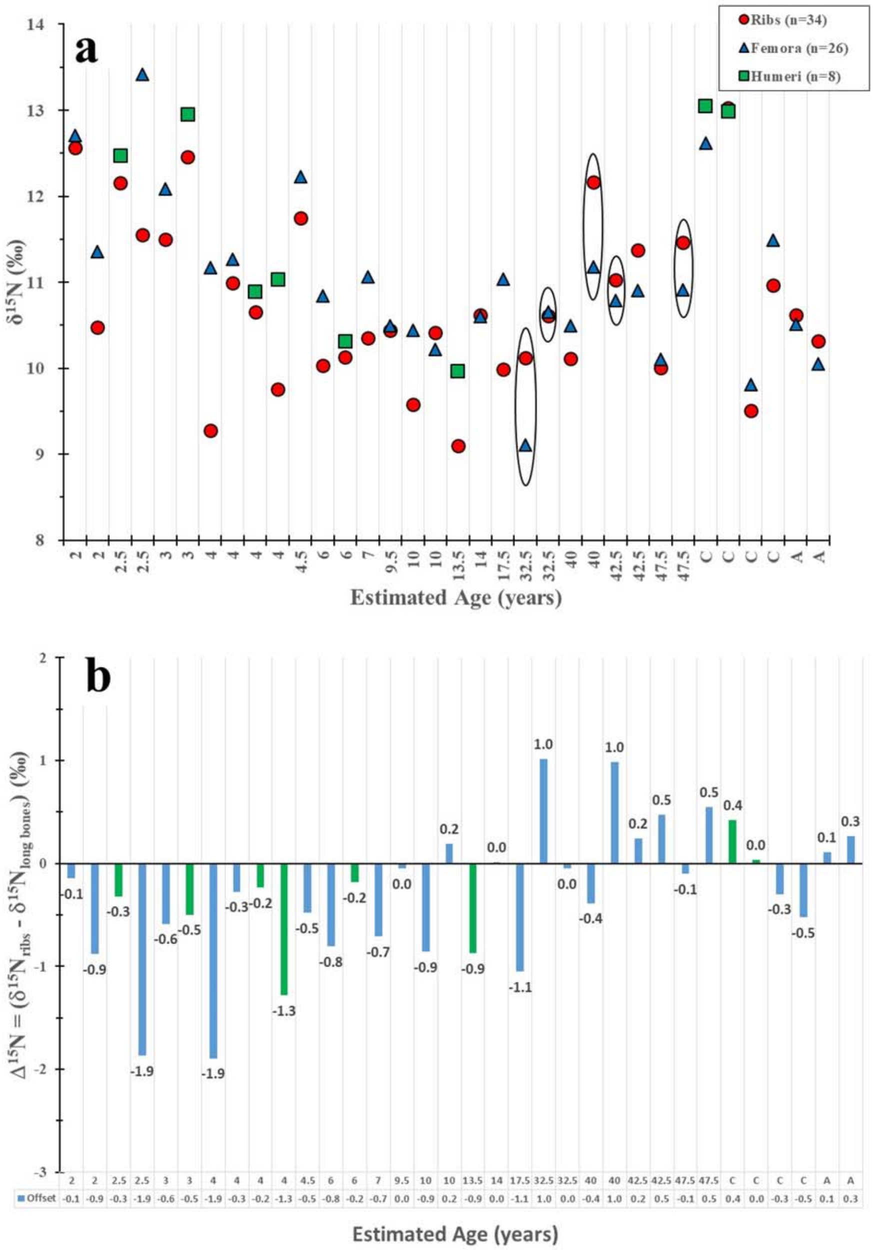


**FIGURE 5** (a) Plot of individual $\delta^{15}$N rib and long bone values versus estimated age at death for all individuals from the Boyangcheng site, Anhui Province, China. (b) Calculated $\delta^{15}$N offsets between ribs and femora/humeri ($\Delta^{15}N = \delta^{15}N_{ribs} - \delta^{15}N_{long\ bones}$) versus estimated age at death for all individuals (blue = femora; green = humeri). Note: C = child of unknown age; A = adult of unknown age

The $\delta^{15}$N values display characteristic patterns of breastfeeding (Tsutaya and Yoneda, 2015), with many infants and young children aged 4.5 years and under showing higher values compared to those of older individuals (Figure 3b). However, the majority of children show values within the standard deviation of the adult mean by the age of 4, suggesting that the weaning process was completed between 3 and 4 years of age, but possibly slightly earlier, given the lag in time associated with bone growth (Richards et al., 2002; Tsutaya and Yoneda, 2013). After the age of 4 years, the $\delta^{15}$N values decrease to within the adult range, except for two individuals (M9 North and South), and this indicates that breastfeeding had ceased at Boyangcheng. However, variability in the $\delta^{15}$N values demonstrates that not all individuals necessarily followed this pattern, and it is worth noting that an infant aged 2 years old (M23) exhibits a relatively low $\delta^{15}$N rib value, which is within the adult range, indicating that weaning was already complete by the age of 2. In addition, some children and adolescents rib $\delta^{15}$N values between 4 and 14 years of age are lower than the adult mean values of the population (Figure 3b). This observation is consistent with some past studies that also found postweaning subadults to have relatively lower $\delta^{15}$N results than the adult mean (Fuller et al., 2006a; Richards et al., 2002).

### 3.4 | Isotopic offsets between ribs and long bones

Both the carbon and nitrogen isotope data of ribs and long bones from the same individual are plotted with estimated age at death in Figures 4a and 5a. In addition, the offsets in the carbon ($\Delta^{13}C = \delta^{13}C_{rib} - \delta^{13}C_{long\ bone}$) and nitrogen ($\Delta^{15}N = \delta^{15}N_{rib} - \delta^{15}N_{long\ bone}$) results of the ribs and femora/humeri are also presented in Figures 4b and 5b. For most individuals, there are no obvious stable carbon isotopic differences between the ribs and long bones, but five adults have significantly higher $\delta^{13}C$ values for their femora compared to their ribs. In addition, four of these same individuals also have lower femora $\delta^{15}N$ values. This indicates that these individuals experienced dietary or residence changes later in their adult lives. In terms of the $\Delta^{15}N$ offsets, the largest isotopic differences between the ribs and long bones, occurs during the weaning period (Figure 5a,b). This is expected as this period reflects a significant change in diet from breastmilk to weaning foods. Between the ages of 2 and 10 years, all individuals show lower rib $\Delta^{15}N$ values, exemplifying the ability of ribs to register changes in diet at a faster rate than long bones (Cox and Sealy, 1997; Sealy, Armstrong, & Schrire, 1995).

## 4 | DISCUSSION

Previous research on the agricultural practices of the Jianghuai region, and archaeological evidence from phytolith and plant flotation studies found that rice agriculture was established and became the dominant grain for humans during the Neolithic period (Yang, 2001; Zhang and Tang, 1996). Although no plant remains were found at Boyangcheng, phytolith analysis from the nearby Heying site (20 km away from Boyangcheng) suggests that rice was the primary food produced in the vicinity of Boyangcheng during the early Western Zhou Dynasty (Wu, Huang, Yao, Gong, & Wang, 2005). Thus, we infer that the $C_3$ isotopic signatures mainly reflect the consumption of rice as the staple grain for this population. However, the wide variety of $\delta^{13}C$ values suggests that the Boyangcheng population had fairly heterogeneous diets, with the adults consuming mixed $C_3/C_4$ diets. This dietary diversity matches well with the complex local culture of this region (see Archaeological and historical background section) and is consistent with previous research that the people during the Western Zhou Dynasty consumed various kinds of foods, such as $C_3$ grains (rice, wheat), $C_4$ grains (millet), vegetables, and fruits (Liu, 2009; Ma, 1984).

In addition, past research determined that millet and rice agriculture were established in north and south China, respectively, as early as the early Neolithic period (Fuller et al., 2009; Jones and Liu, 2009; Liu, Lee, Jiang, & Zhang, 2007; Zhao, 2011). However, millet agriculture then expanded southwards, while rice agriculture diffused northwards, from ~7000 to 5500 BP, and this movement caused the formation of the rice–millet blended zone where both rice and millet was cultivated between the Yangtze River and Yellow River Valleys (Fu et al., 2010; Guo et al., 2011). For example, both rice and millet agricultural remains have been found at the Yuchisi (4600 BP) and Yuhuicun (4500–4000 BP) sites of Anhui province (Wang and Wu, 1998; Xu, 2013). At Boyangcheng the isotopic results of the humans show that individuals preferred to consume rice but were more likely to feed their domestic animals (cattle, horses, and some pigs) with millet, and similar subsistence practices were also found at other sites of the rice–millet blended zone of China (Chen, Luo, Hu, Zhu, & Wang, 2015; Fu et al., 2010; Guo et al., 2011; Ma et al., 2016a).

While the rate of bone collagen turnover in healthy adult humans is not precisely known and can be influenced by factors such as nutritional status, disease and age, small/thin cancellous (spongy) bones such as ribs have been found to turnover more rapidly than dense compact long bones (Cox and Sealy, 1997; Hedges et al., 2007; Parfitt, 2002). As a result, ribs are more sensitive to recent dietary changes and are considered an appropriate skeletal element to investigate breastfeeding and weaning practices (Richards et al., 2002; Tsutaya and Yoneda, 2015). However, it is also possible to obtain additional information about the life history of an individual by comparing multiple bones with different turnover times. The isotopic analysis of different skeletal elements to reconstruct individual life histories was successfully demonstrated by a number of past studies (Bell, Cox, & Sealy, 2001; Chenery, Lamb, Evans, Sloane, & Stewart, 2014; Cheung, Jing, Tang, Weston, & Richards, 2017; Cox and Sealy, 1997; Jørkov, Heinemeier, & Lynnerup, 2009; Lamb, Evans, Buckley, & Appleby, 2014; Pollard et al., 2012; Schroeder, O'Connell, Evans, Shuler, & Hedges, 2009; Sealy et al., 1995), and some of these studies utilized the differences in bone turnover rates to explore dietary or residence changes in individuals over time. However, only a few studies focused specifically on rib-femora isotopic offsets and examined a large number of individuals (Chenery et al., 2014; Cheung et al., 2017; Jørkov et al., 2009; Pollard et al., 2012).

Here at Boyangcheng, it is notable that five adults were found to have femora with elevated $\delta^{13}C$ values compared to their ribs. This indicates that these individuals experienced drastic dietary changes later in their adult lives, all switching from diets with mixed $C_3/C_4$ resources to more $C_3$-predominate diets. In addition, four of these five individuals also have femora that are lower in $\delta^{15}N$ compared to their ribs. This could suggest that the type or the amount of animal protein consumed by these individuals increased in later life. At the present time, it is unknown what circumstances or situations influenced these five individuals to alter their diets. However, examination of the isotopic signatures of the animals suggests that these five individuals might have changed their diets from cattle and pigs fed millet to pigs that were fed rice and wild pigs and deer. As only evidence of rice agriculture was uncovered in the vicinity of Boyangcheng (this does not mean that millet agriculture was not present as no flotation studies were done during the rescue excavation at Boyangcheng), this could suggest that animals consuming millet were coming from other sites, possibly northern China as a result of trade. Additional isotopic studies of the animals involving sulfur or strontium would be necessary to test this possibility, and this is an area of future research (Towers, Montgomery, Evans, Jay, & Pearson, 2010; Towers, Jay, Mainland, Nehlich, & Montgomery, 2011).

It is also highly possible that these five individuals represent migrants to Boyangcheng from a more $C_4$ dietary environment in the north of China. As millet and rice agriculture were established in north and south China respectively, individuals who migrate between these $C_4$ and $C_3$ zones can potentially experience a dietary change and exhibit this in their bone collagen isotopic ratios. This isotopic approach was previously used by Ma et al. (2016a) to examine the origins of workers and prisoners that built the mausoleum complex for the First Emperor of China (Qin Shi Huang, 259–210 BC). The possibility that these five individuals migrated to Boyangcheng is consistent with the historical accounts and archaeological evidence that the Dongyi from the Shandong area moved to the Jianghuai region due to their long-running conflicts with the Western Zhou Dynasty (Figure 1b). However, again, additional isotopic research involving sulfur, strontium or the analysis of dentin serial sections would be necessary to validate this possibility (Beaumont, Gledhill, Lee-Thorp, & Montgomery, 2013; Beaumont and Montgomery, 2016; Cheung et al., 2017; Ma et al. 2016b; Wang et al., 2016).

In addition, by comparing the rib and long bone $\Delta^{13}C$ and $\Delta^{15}N$ values it is possible to get a more detailed understanding of individual breastfeeding and weaning patterns. For example, the infant M13 (2 years old) shows high rib (12.6‰) and femora (12.7‰) $\delta^{15}N$ values with a negligible $\Delta^{15}N$ offset (0.1‰). This indicates that M13 was still being significantly breastfed at her/her time of death. However, the rib $\delta^{13}C$ result (−19.2‰) is lower by 1‰ compared to the femur (−18.2‰), and this is evidence that M13 was already introduced to solid foods and died during the early stages of the weaning process. Further, large $\Delta^{15}N$ offsets can show that individuals were nearly fully weaned off breastmilk at the time of death (e.g., M22 (2.5 years old); M8(A)big (4 years old); M37 (4 years old)). While these individual results are variable, they support the observation that breastfeeding continued until 3–4 years of age and that weaning was generally completed by that age of 4 years. This information from both ribs and long bones can help with the reconstruction of individual specific weaning patterns and aids in the understanding of infant feeding practices at an archaeological site, and we recommend this approach for future breastfeeding/weaning studies in China.

As the earliest historical Chinese text about infant feeding practices and childhood diet, *Qianjinfang* (千金方) recommended exclusive breastfeeding should last for ~6 months and that complementary food such as porridge could be introduced after 6 months (Sun, 1993). The writer Simiao Sun also believed that it was not appropriate to prolong breastfeeding past 2–3 years as a later weaning period would damage the long-term health of children. Furthermore, he recommended a more plant-based diet for young children, and believed that meat should not be added to the diet of a child until 5 years of age (Sun, 1993). At Boyangcheng, these lower $\delta^{15}N$ values appear to reflect a more plant-based diet during early or middle childhood (Reitsema and Muir, 2015). This finding is consistent with the recommendations of Simiao Sun of the Tang Dynasty (over 1500 years later), and could suggest that this was a general practice of infant feeding in ancient China. It is also interesting that these lower $\delta^{15}N$ values reflecting plant based diets of children likely did not contain the addition of significant amounts of dairy products such as milk. This may have been a deliberate decision of the inhabitants of Boyangcheng given the prevalence of lactose intolerance in modern and likely ancient Chinese populations (Yang, He, Cui, Bian, & Wang, 2000; Yang et al., 2013). This type of weaning regime may have influenced child health and nutrition patterns in ancient China compared to Europe, and more research linking isotopic and ancient DNA studies related to milk consumption in ancient China are needed in future to better understand the complexities of infant feeding and childhood diets across Eurasia.


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