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Dietary adaptation during the Longshan period in China: stable isotope analyses at Liangchengzhen (southeastern Shandong)

Rheta E. Lanehart[a,*], Robert H. Tykot[a], Anne P. Underhill[b], Fengshi Luan[c], Haiguang Yu[c], Hui Fang[c], Cai Fengshu[c,1], Gary Feinman[d], Linda Nicholas[d]

[a] Department of Anthropology, University of South Florida, 4202 E. Fowler, Tampa, FL 33620, USA
[b] Department of Anthropology, Yale University, 10 Sachem St., New Haven, CT 06511, USA
[c] School of History and Culture, Shandong University, 27 Shanda Nanlu, Jinan City, Shandong, China
[d] Department of Anthropology, The Field Museum, 1400 S. Lake Shore Dr., Chicago, IL 60605, USA

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ABSTRACT

Rice and millet were staple crops at Liangchengzhen, a late Neolithic Longshan site in Shandong, China, but the degree of dietary variation is not known. This study uses stable isotope analysis of human and faunal skeletal remains to quantitatively address the importance of these crops as well as terrestrial domesticates and aquatic resources in the diet at Liangchengzhen. Although no collagen could be extracted from the poorly preserved human bones, the $\delta^{13}C$ stable isotope results for 2 apatite sample and 16 tooth enamel samples averaged −9.8‰ suggesting that diet was based on foods averaging from −24‰ to −18‰, with millet and millet-fed animals comprising at most approximately 25–30% of the diet. Pig faunal $\delta^{13}C$ isotope values suggested that during the earlier Longshan period pigs were fed mainly millet with more C_3 foods such as rice included by the later Longshan period. Solid ceramic residues from two *guan* jar sherds produced $\delta^{13}C$ values averaging −18‰ and $\delta^{15}N$ values averaging +16‰, suggesting both vessels contained fish. The results of the study indicate that by the Longshan period, people in southeastern Shandong no longer relied as heavily on millet and that the agricultural crop of rice had increased in importance at Liangchengzhen. Unfortunately, without human collagen samples to provide nitrogen isotope results, we cannot estimate the relative contribution of aquatic and terrestrial protein to the diet of people at Liangchengzhen. In general, however, the pattern of a diverse agricultural system on the basis of the macrobotanical remains from Liangchengzhen is supported by the isotopic results.

1. Introduction

In northern China by the late Neolithic period, diets were based on domesticated plants and animals, but the degree of dietary variation is not known. In particular, most scholars have thought that rice was first domesticated and remained important in southern China while millet was first domesticated and became the dietary staple in northern China (Chang, 1986; Crawford et al., 2005). Major questions remain, however, about the spread of these domesticates into other regions, and at what times. Studies of the archaeobotanical remains from the recently excavated site of Liangchengzhen in southeastern Shandong province (Crawford et al., 2004, 2005) demonstrate that rice (*Oryza sativa*) and millet (both *Setaria italica* and *Panicum miliaceum*) were staple crops in that region during the Longshan period. Our study, using isotope analysis of human and faunal skeletal remains, was specifically designed to quantitatively address the importance of each of these crops in the diet of people living at Liangchengzhen. Stable carbon and nitrogen isotope analysis is a well established technique for determining the dietary contributions of terrestrial and marine foods, as well as C_4 plants in otherwise C_3 systems. Our continuing isotopic analyses provide complementary quantitative data to assess the relative importance of these isotopically diverse food groups, in addition to preliminary data that identify residues from ceramic sherds.

2. Diet in ancient China

During the last 15 years, more information about regional variation (Fig. 1) in dietary and agricultural practices during the Neolithic period of China has become available (Barton et al., 2009; Cohen, 1998; Crawford et al., 2004, 2005; Crawford, 2006, 2009; Hu et al., 2006, 2008; Jin, 2009; Liu et al., 2007; Lu, 1999; Lu et al., 2009;

* Corresponding author. Tel.: +1 813 974 2138; fax: +1 813 974 2668.
E-mail address: rlanehar@usf.edu (R.E. Lanehart).
[1] Deceased.

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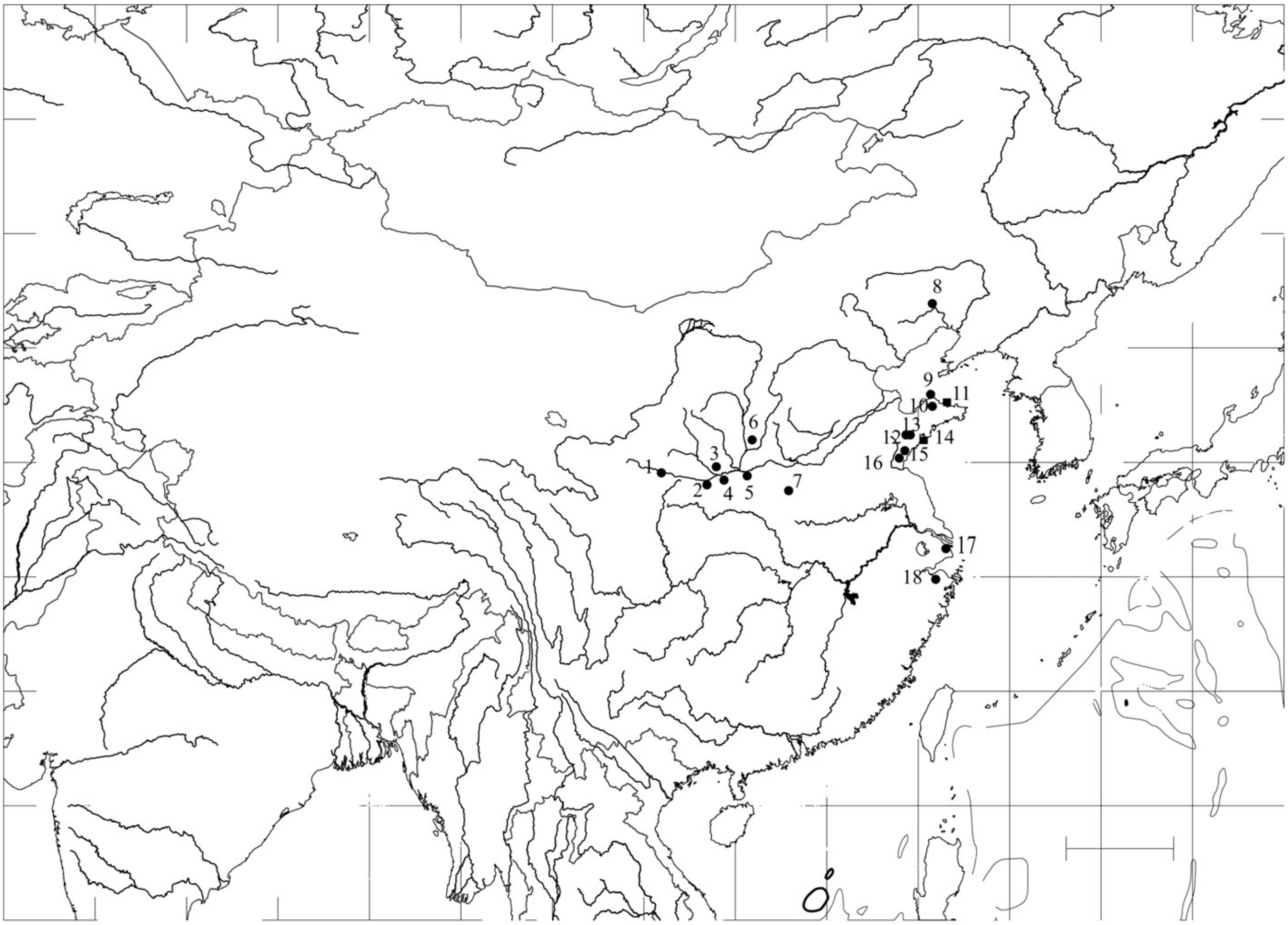

Fig. 1. Sites in China with stable isotope data. 1. Dadiwan; 2. Jiangzhai; 3. Kangjia; 4. Shijia; 5. Xipo; 6. Taosi 7. Jiahu; 8. Xinglongwa; 9. Beizhuang; 10. Guzhendu; 11. Yantai (Modern isotope values from shellfish); 12. Zhujiacun; 13. Lingyanghe; 14. Qingdao (Modern isotope values from shellfish); 15. Liangchengzhen; 16. Yaowangcheng; 17. Songze; 18. Hemudu.

Pechenkina et al., 2002, 2005; Qi et al., 2004; Underhill, 1997, 2002; Underhill and Habu, 2006; Zhang et al., 2003, Zhao, 1998, 2010). In particular, the expanded and systematic application of flotation to collect macrobotanical remains has yielded evidence that dietary practices were more diverse than realized, with a considerable range in northern China alone (e.g., Crawford et al., 2005; Lee et al., 2007). In Shandong province, both millet and rice have been found at a number of sites from the early to late Neolithic periods, including Longshan period sites, ca. 2600–1900 B.C. (Crawford et al., 2004, 2005, 2006; Hu et al., 2006, 2008; Jin, 2009).

2.1. Millet

Indigenous agriculture in China included domesticated crops of broomcorn (*P. miliaceum*) and foxtail (*S. italica)* millets (Crawford, 2006; Lu, 2006). It appears that domesticated millet was the primary crop grown and cultivated during the Neolithic for North China as a whole with broomcorn millet most important early in that period.

Evidence of domesticated millet was first found in the early Neolithic cultures (formerly regarded as ca. 6000–5000 B.C.; earliest phase recently redated to ca. 8000 B.C., see Crawford, 2009; Lu et al., 2009) of Peligang (Yellow River Basin), Xinglongwa (Northeast), and Laoguantai (West) and the Houli–Beixin periods (ca. 6500–4100 B.C.) in Shandong (Lee et al., 2007; Luan and Wagner, 2009). Flotation samples from the Yuezhuang (Houli culture) and Xinglonggou (Xinglongwa culture) sites indicated that broomcorn millet was the main crop with foxtail millet sparsely present (Crawford et al., 2005; Lee et al., 2007).In a reanalysis of grains from the Peiligang site of Cishan broomcorn millet was found to be the dominant crop during the earliest two occupation phases (Crawford, 2009; Lu et al., 2009). By the Late Peligang/early Yangshao, however, the dominance of foxtail millet over broomcorn millet had been established (Lee et al., 2007).

Millet continued as the primary grain during the Yangshao (ca. 5000–2800 B.C.) and Dawenkou (ca. 4300–2600 B.C.) periods (Crawford, 2006). During the Longshan, the types of cultivated millet varied by region, i.e. broomcorn millet was more common in the drier central regions of the north, e.g. the Yi-Lou area of Henan province, and foxtail millet was more abundant in the wetter eastern regions, e.g. Shandong. However, foxtail millet was cultivated more widely overall (Lee et al., 2007). With agricultural intensification, millet may have been used as fodder for domesticated animals (Crawford, 2006; Pechenkina et al., 2005; Yuan and Flad, 2002).

2.2. Rice

The increasingly abundant research on the origins of rice (*O. sativa*) farming continues to reveal a pattern of early cultivation in at least one region of the Yangzi River Valley in southern China. The earliest domesticated remains of rice in this area to date were recovered at the site of Shangshan in Zhejiang province, lower Yangzi river valley (Liu et al., 2007).

Until recently it was thought that the cultivation of rice was rare in North China and arrived either as an introduced crop or by trade (Barton et al., 2009; Lee et al., 2007; Underhill, 1997). Carbonized rice grains were found at the early Neolithic site of Jiahu, in Henan province (ca. 7000-5800 B.C.) located on the border of the northern/southern subtropical zone (Hu et al., 2006). However, the earliest cultivated rice (*O. sativa*) seeds from flotation sediment in North China were found at the Houli Culture site of Yuezhuang, Jinan city, Shandong province. An AMS radiocarbon date of 7050 ± 80 B.P. (6060-5750 cal B.C. at 2 sigma) indicated that rice was cultivated in the lower Yellow River valley area 2000 years earlier than previously recorded (Crawford et al., 2006).

Rice grains have been found at a handful of sites dating to the late Dawenkou and Longshan periods (Crawford et al., 2005; Jin, 2009). Phytolith analysis on samples from a rice paddy at the Longshan site of Zhaojiazhuang (ca. 2600-2300 B.C.), located in a coastal area of Shandong province, have indicated the practice of rice agriculture (Jin et al., 2007).

2.3. Fauna

The earliest domesticate in northern China appears to be the dog, followed by pigs, chickens, cattle, sheep, and goats (Barton et al., 2009; Jin, 2009; Lee et al., 2007; Underhill, 1997; Yuan and Flad, 2002). This sequence will be refined as more projects systematically collect faunal remains.

3. Liangchengzhen

Liangchengzhen is a Longshan period site in the Rizhao district of southeastern Shandong. A previous systematic, regional survey found that Liangchengzhen was a large regional center of a four-tiered settlement hierarchy (Fang et al., 2002, 2008; Underhill et al., 2002, 2008). Established along the major Bei Xiao He/Chao He river system during the early Longshan period, Liangchengzhen grew to its maximal extent by the middle Longshan period (sherd surface coverage, ca. 250 ha and extent of remaining cultural deposits ca. 100 ha). Liangchengzhen was one of the largest settlements in northern China during the late Neolithic (Luan et al., 2004).

A collaborative Sino–American excavation involving participants from Shandong University, Yale University, and The Field Museum took place from October–December, 1999–2001. The main excavation area (704 m^2) is situated on a slightly raised area approximately 12 m above and 600 m west of the Bei Xiao He (Fig. 2). Large Longshan settlements in northern China tended to have residential areas that included elite and lower-class houses, burials, pits utilized for refuse and ritual, and larger features such as earthen walls and surrounding ditches that might have been moats (see Liu, 2004). In the main excavation area at Liangchengzhen, the context types were diverse but primarily domestic and likely indicate non-elite households (Crawford et al., 2005; Luan et al., 2004).

Macrobotanical remains, including both rice and millet, were recovered. Rice (*O. sativa*) was the most common cultigen based on the density, number, and weight of seeds recovered (Crawford et al., 2004, 2005). Millet (*S. italica*) occurred at a lower density than rice with foxtail millet accounting for 94% of the millets at Liangchengzhen. Phytolith analysis of soil samples from ash pits and cultural layers at Liangchengzhen also indicated an abundance of rice, *O. sativa*, ssp. *japonica* (Jin et al., 2004).

Based on discoveries at other Longshan period sites in Shandong, the geographic location of Liangchengzhen, analysis of faunal remains from the excavation, and the diet of its modern residents, we expect that the residents of the Longshan period regional center also would have consumed domesticated animals such as pig, and both riverine and marine resources. The limited sample of well preserved, identifiable faunal remains at Liangchengzhen reveals a heavy reliance on pigs (Bekken, n.d.). Our continuing research on subsistence at Liangchengzhen during the Longshan is an attempt to assess the relative importance of millet and rice as well as terrestrial domesticates and aquatic resources.

4. Stable isotope analysis

Stable isotope analysis can differentiate between C_3 and C_4 terrestrial diets in humans and animals. C_3 plants such as rice have a $\delta^{13}C$ value averaging about −26‰, whereas C_4 plants such as millet have $\delta^{13}C$ values averaging −14‰. Nitrogen isotope ratios ($\delta^{15}N$), which are generally similar among plants, do increase with trophic level, and are also generally higher in aquatic than in terrestrial systems. These natural differences in carbon and nitrogen isotope ratios of plants and animals are passed on to their human consumers, and thus archaeological samples of bones and teeth may be analyzed to measure the relative importance of isotopically diverse food groups.

4.1. Carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes

Carbon isotope ratios may be measured in two different bone tissues - collagen (a protein) and apatite (the bone and tooth mineral) - while nitrogen is only present in collagen. Controlled dietary studies have demonstrated that the $\delta^{13}C$ values of collagen mainly reflect the contribution of dietary protein in a monoisotopic diet (e.g., solely C_3 or C_4), while bone apatite and tooth enamel reflect the whole diet regardless of a mono or mixed isotopic diet (e.g. Ambrose and Norr, 1993; Kellner and Schoeninger, 2007; Tykot et al., 2009). In addition, bone collagen and apatite are constantly resorbed and regenerated, and thus reflect diet over at least the last several years of an individual's life, while tooth enamel apatite reflects diet only during the age of crown formation. Metabolic processes in the formation of these tissues result in isotopic fractionation, so that collagen is enriched about 5‰ in $\delta^{13}C$ (Tykot et al., 2009) and 3‰ in $\delta^{15}N$ (Hedges and Reynard, 2007), while bone and tooth enamel apatite are enriched about +12‰ in $\delta^{13}C$, although the diet-bone apatite spacing is not as straightforward as collagen.

Experimental models have shown that $\delta^{13}C$ apatite fractionation varies with different animal species ranging from +8‰ to +14‰ (Ambrose and Norr, 1993; Howland et al., 2003; Jim et al., 2004; Kellner and Schoeninger, 2007; Kreuger and Sullivan, 1984; Passey et al., 2005; Tieszen and Fagre, 1993; Tykot et al., 2009). Pigs fed varying combinations of C_3/C_4 diets had a $\delta^{13}C$ diet-apatite spacing ($\Delta\ \delta^{13}C_{\text{diet-apatite}}$) that ranged from +8.7‰ to +12.1‰, with an average of 10.2 ± 1.3 ‰ (Howland et al., 2003). Pig tooth enamel-diet spacing ($\Delta\ \delta^{13}C_{\text{diet-enamel}}$) averaged 13.3 ± 0.3‰ (Passey et al., 2005). Harrison and Katzenburg (2003) consider the "best fit" for whole diet spacing in humans to be +12‰, while Prowse et al. (2004) postulate +13‰.

4.2. Oxygen ($\delta^{18}O$) isotopes

Stable oxygen isotope ($\delta^{18}O$) values can provide information about geographical origin (Dupras and Schwarcz, 2001). Oxygen isotopes in water carry a geographic signature that is represented in the bones and teeth of persons who ingest water from their surrounding habitat. The $\delta^{18}O$ isotopic composition of body water is primarily influenced by the ingestion of local meteoric precipitation which is affected by a locale's climate and geography (White et al., 1998). Additional factors that affect oxygen isotope values of mammalian body water include atmospheric oxygen, oxygen of

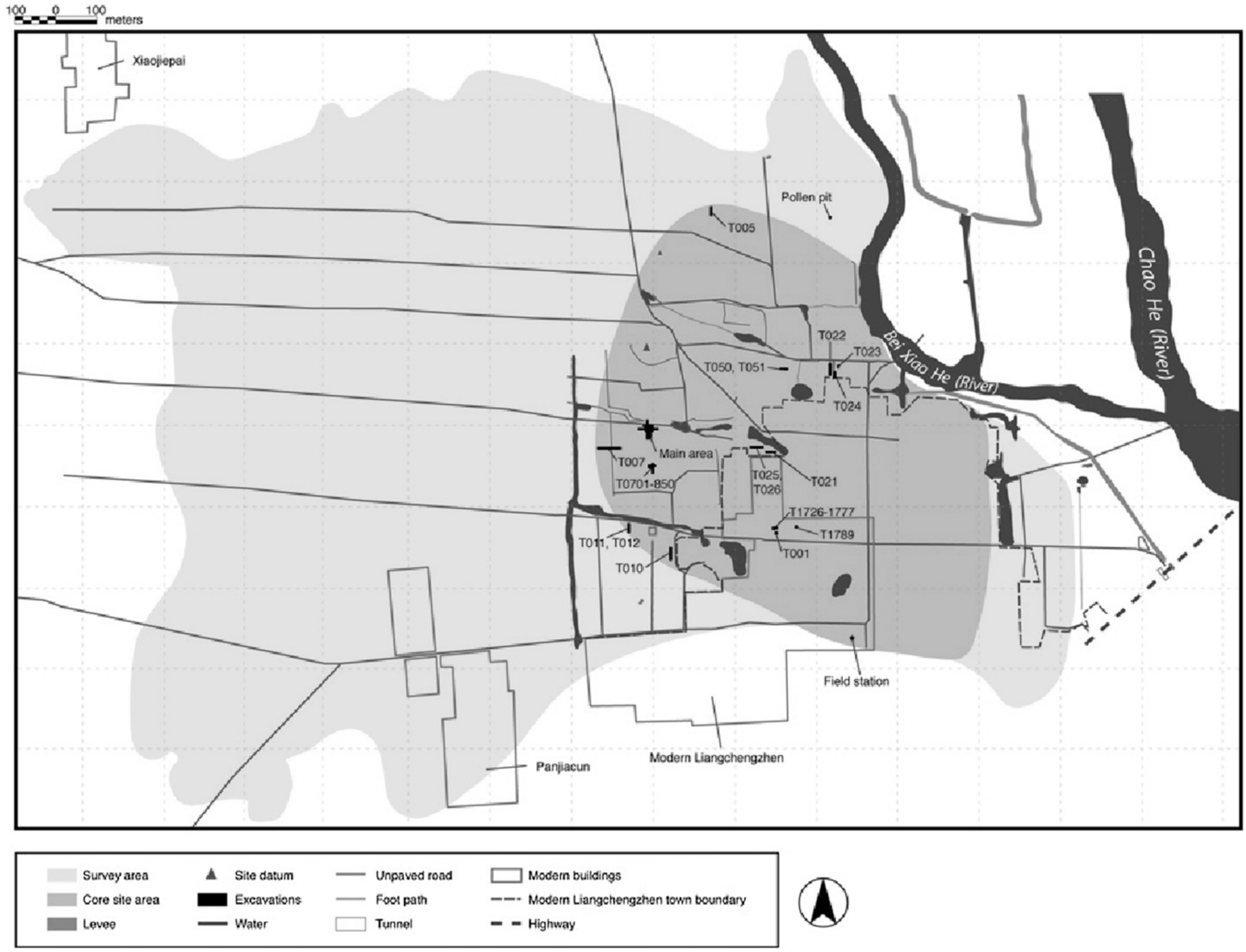

Fig. 2. Liangchengzhen archaeological site.

organic food compounds, and physiological variation (Luz et al., 1990; Sponheimer and Lee-Thorp, 1999). Bone and teeth reflect oxygen isotope values at the time of mineralization in childhood and early adulthood (Luz et al., 1984). Dental enamel will mirror isotopic values of the geographic region where the enamel mineralization occurred. Oxygen isotope values in bone mineral comprise an extended average of remodeling and are similar to the turnover rate of collagen (Dupras and Schwarcz, 2001; Luz and Koldony, 1989). Oxygen isotopes occur in archaeological bone and tooth enamel as phosphate and carbonate oxygen. In bone, phosphate oxygen is less susceptible to diagenetic processes, while carbonate oxygen is unstable (Luz and Koldony, 1989; Sponheimer and Lee-Thorp, 1999). Carbonate in ancient enamel, however, is conserved due to enamel's higher density and crystallinity (Sponheimer and Lee-Thorp, 1999).

5. Materials and methods

5.1. Previous analyses

Our initial stable isotope analysis during 2002 involved two human enamel samples (ID 5983 & 5988) and a single faunal (pig) molar sample (ID 7969) as well as surface residues from 2 *guan* jars (ID 6018 & 6019) from Liangchengzhen (Table 1). At the same time, a reference dataset for interpreting human results was established by analysis of tissue from 27 modern marine and freshwater fish and rice grains from the Rizhao area in Shandong (Table 2).

5.2. Current analysis of excavated samples

The present analysis of human remains focuses on the enamel from thirteen individual teeth plus two bone apatite samples from the Longshan and one tooth enamel sample from a post-Longshan Western Zhou period (ca.1046–771 B.C.) context at the site (Table 1). Analysis of faunal remains focus on enamel and apatite from 4 pigs and 1 dog, all from the Longshan.

The sampling strategy for the analysis was based upon availability since the preservation of animal and human bone was very poor, probably due to water retention in the clayey soil. Unfortunately, no collagen could be extracted from the poorly preserved human bone, and in all but two cases not even the bone apatite was preserved for a reliable analysis. Nevertheless our initial study provides hypotheses that warrant further investigation.

The majority of human bone samples were from burials within the main excavation area ($n = 11$) with only a few ($n = 4$) originating from external trench areas (Figs. 2 and 3, Table 1; Clark, n.d.). Faunal samples from the main excavation area ($n = 3$) were from a house and 2 pits while the remaining faunal samples ($n = 2$) were from the external trench areas.

Table 1
$\delta^{13}C$ and $\delta^{18}O$ stable isotope values for human, faunal, and ceramic archaeological samples.

Human samples

Burial	Source	ID	[a]Site Longshan phase	Context (grid unit)	$\delta^{13}C$	$\delta^{18}O$
M46, adult male, 25–40	Molar enamel	7389	Early	T2400	−12.1	−5.9
M49, adult male, 30–40	Enamel (M3)	7400	Early	T2400	−12.3	−5.7
M60, unknown sex & age	Tooth enamel	5988	Early	T2299	−11.1	−5.4
M61, unknown sex & age	Bone apatite	5990	Early	T2350	−9.3	−6.5
M68, unknown sex, 12–14	Tooth enamel	7397	Early	T2349	−10.8	−4.6
M70, female over 18	Molar enamel	7392	Early	T2299	−9.4	−5.2
M24, unknown sex & age	Tooth enamel	5983	Middle	T2350	−9.7	−5.8
M33 adult male, 35–45	Tooth enamel	7396	Middle	T2396 & 2397	−6.5	−6.1
M44, child 4–6	Molar enamel	7388	Middle	T2449	−11.4	−4.1
M50 male, 34–36	Enamel (M2)	7402	Middle	T021[c]; trench area	−9.5	−5.5
M50, male, 34–36	Apatite	7404	Middle	T021[c]; trench area	−7.8	−6.0
M51, female, 30–35	Molar enamel	7408	Middle	T021[c]; trench area	−9.5	−5.1
M66 female, over 55	Molar enamel	7407	Middle	T024[c]; trench area	−10.2	−5.9
M21, adult, probably male	Molar enamel	7391	Late	T2997 & T2998	−7.3	−5.8
M22, adult, unknown sex, over 30	Tooth enamel	7394	Late	T2344	−12.4	−5.1
M23, badly preserved, age/sex unknown	Tooth enamel	7390	Late	T2447	−10.3	−5.4
M38, badly preserved, age/sex unknown	Tooth enamel	7399	Late	T2400	−10.8	−5.3
M15, unknown	Molar enamel	7395	Post-Longshan [Zhou]		−6.6	−5.4
				Mean ± SD	−9.8 ± 1.8	−5.5 ± 0.6

Faunal samples

Feature	Source	ID	[a]Site Longshan phase	Context (grid unit)	$\delta^{13}C$	$\delta^{18}O$
House F65, pig	Tooth Enamel	7969	Early	T2296; Small round house	−0.1	−7.9
Cultural Layer, dog	Apatite	7970	Middle	Trench area[c]	−8.7	−8.1
Moat, pig	Apatite	7972	Middle	Trench used as inner moat[c]	−4.1	−7.9
Pit H405, pig	Tooth Enamel	7968	Middle	T2296; Small pit	−4.2	−7.5
Yaowangcheng, pig	Apatite	7746	[b]Middle		−7.1	−3.1
Pit H31, pig	Tooth Enamel	7974	Late	T2350; Richest pit at Liangchengzhen; ritual remains	−10.9	−6.0
				Mean ± SD	−5.6 ± 4.2	−7.5 ± 0.9

Ceramic residues

Feature	Source	ID	Site Longshan phase	Context (grid unit)	$\delta^{13}C$	$\delta^{15}N$
H349	Guan jar sherd	6018	Middle	T2345	−17.5	17.7
H349	Guan jar sherd	6019	Middle	T2345	−18.6	15.0
				Mean ± SD	−18.1 ± 0.8	16.4 ± 1.9

[a] These phases refer only to the Liangchengzhen site. The Early phase at Liangchengzhen falls within the latter half of the Early Longshan Period (Early Longshan II) for Shandong province as a whole. The Middle and Late phases at Liangchengzhen fall within the Middle Longshan Period for Shandong province as a whole (Middle Longshan III and Middle Longshan IV).
[b] The sample recovered from the Yaowangcheng site during survey is estimated as being contemporary with our Liangchengzhen site Middle phase. Yaowangcheng isotope value not included in the faunal Mean ± SD.
[c] Located outside of the main excavation area. Yaowangcheng is located south of Liangchengzhen.

5.3. Fish sample preparation

Dehydrated fish samples, initially acquired fresh from the Shandong area, were re-hydrated in water at the Laboratory for Archaeological Science, University of South Florida. A small amount of fish tissue was excised using a scalpel and placed in a tin cup for $\delta^{13}C$ and $\delta^{15}N$ collagen analysis by stable isotope mass spectrometry.

5.4. Ceramic surface residue extraction

Surface residues were removed from the *guan* jar sherds using forceps and extracted by vacuum aspiration with a 500 ml Pyrex side arm flask. Briefly, tubing was attached to the flask sidearm and an aspirator faucet attachment. Solid residues from the *guan* jars were placed in a Coors ceramic funnel (186 mL) lined with Whatman filters (70 mm) on top of the sidearm flask. Water from the pressurized faucet rose through the filter breaking the solid residues inside the funnel into fragments. After the residue fragments were removed from the funnel using forceps and allowed to air dry, they were selected for mass spectrometry analysis by microscopic examination.

5.5. Enamel and apatite extraction

All human and faunal samples in the study (Table 1) were prepared at the Laboratory for Archaeological Science in the Department of Anthropology using an established protocol to remove nonbiogenic carbon contaminants and for the chemical extraction of apatite from tooth enamel and bone samples (Koch et al., 1997; Tykot et al., 2009). Briefly, bone fragments and tooth samples (~1g) were cleaned using ultrasonic vibration and distilled water. Approximately 10 milligrams of drilled powder from the cleaned apatite and enamel samples was treated by the removal of organic components using bleach (24 hours for enamel, 72 hours for apatite), and of nonbiogenic carbonates using buffered 1M acetic acid (24 hours). Following rinsing, drying, and weighing to measure the yield, 1 mg samples were selected for analysis on the mass spectrometer.

5.6. Measurement of stable isotope ratios

Stable isotope analysis by mass spectrometry was performed at the Stable Isotope Paleolaboratory, also at the University of South Florida, using a Finnegan MAT Delta Plus equipped with a Kiel III input device. Results for carbon and oxygen isotopes are calibrated against international standards, and typically have a precision of ±0.1‰.

Table 2
$\delta^{13}C$ and $\delta^{15}N$ stable isotope values for modern reference fish and rice samples.

Species	Fish samples			
	Source	ID	$\delta^{13}C$	$\delta^{15}N$[b]
Platycephalidae (flathead)	SW	5991	−17.2	11.4
Unknown	SW[a]	5992	−16.6	12.7
Unknown	SW[a]	5993	−16.0	13.5
Unknown	SW[a]	5994	−16.6	12.8
Unknown	SW[a]	5995	−15.2	19.7
Unknown	SW[a]	5996	−21.0	12.7
Lophilidae (goosefish)	SW	5997	−17.1	13.9
Congridae or *Ophicthyidae*	SW	5998	−17.4	12.5
Congridae or *Ophicthyidae*	SW	5999	−17.0	16.0
Congridae or *Ophicthyidae*	SW	6000	−17.4	13.1
Stichaeidae (blenny-like fishes)	SW	6001	−20.3	12.6
Unknown	SW[a]	6002	−16.7	
Unknown	SW[a]	6003	−19.4	
Stomatopoda Crustacean (mantis shrimp)	SW	6004	−17.7	
Stomatopoda Crustacean (mantis shrimp)	SW	6005	−17.3	
Cichlidae	FW	6006	−24.5	
Triglidae (sea robins)	BW–SW	6007	−24.5	
Carangidae (Jacks-scads)	SW	6008	−20.8	
Unknown	SW[a]	6009	−17.8	
Cynoglossidae (tonguefish)	BW–SW	6010	−16.8	
Cynoglossidae (tonguefish)	BW–SW	6011	−17.9	
Cynoglossidae (tonguefish)	BW–SW	6012	−18.6	
Monocanthidae (filefish)	SW	6013	−19.3	
Bramidae (pomphret)	SW	6014	−17.9	
Sparidae (porgy)	BW–SW	6015	−17.8	
Scaenidae (drum)	BW–SW	6016	−16.4	11.9
Unknown	SW[a]	6017	−17.0	11.8
		Mean ± SD	−18.2 ± 2.3	13.4 ± 2.2
Rice sample				
Unknown	Modern	6637	−24.6	5.2

Key: SW = Saltwater; FW = Freshwater; BW–SW = Brackish water-Saltwater.
[a] Source tentatively identified.
[b] Only identified marine species with $\delta^{15}N$ isotope values were included in Fig. 5

6. Results

6.1. Carbon ($\delta^{13}C$) isotopes

The positive (−0.1‰) $\delta^{13}C$ value obtained for an early site phase pig molar at Liangchengzhen (Fig. 4) demonstrates consumption of C_4 foods such as millet, either cultivated or wild grasses. The Liangchengzhen pig apatite $\delta^{13}C$ values from the middle site phase were −4.2, −4.1, and −7.1‰ and the canine $\delta^{13}C$ apatite value was −8.7‰. The pig molar from the late site phase at Liangchengzhen was −10.9‰. The pig apatite value at Yaowangcheng (−7.1‰), another large Longshan site 29 kilometers south of Liangchengzhen (Figs. 1 and 4; see Fang et al., 2008; Underhill et al., 2008), is consistent with the faunal values at Liangchengzhen.

The modern rice sample tested, $\delta^{13}C = -24.6$, $\delta^{15}N = 5.2$, along with a published value for millet, $\delta^{13}C = -13.3$, $\delta^{15}N = 5.6$ (Cai and Qiu, 1984), indicates that the values for C_3 and C_4 plants are about the same in China as elsewhere (Fig. 5).

The isotope results for the two human apatite and 16 tooth enamel samples average −9.8‰ (ranging from −12‰ to −6‰) and suggest that diet was based on foods ranging from −24‰ to −18‰ (Table 1, Fig. 4, Fig. 5).

The data thus far indicate stability in the diet from the later Longshan to the Western Zhou period at Liangchengzhen. The $\delta^{13}C$ isotope value ($\delta^{13}C = -6.6$) for the single Zhou period sample (# 7395) suggests no change in dietary subsistence from the Longshan period (Fig. 4), possibly representing a time period of up to 1000 years.

6.2. Oxygen ($\delta^{18}O$) isotopes

The $\delta^{18}O$ stable isotope values for faunal samples were −7.9‰ during the early site phase and averaged −7.8‰ (−7.5‰ to −8.1‰) during the middle site phase. The pig sample from late site phase pit H31 has an $\delta^{18}O$ value of −6.0‰ similar to human $\delta^{18}O$ values. The $\delta^{18}O$ value (−3.1‰) of the faunal sample from Yaowengcheng suggests a different geographic locale.

Human $\delta^{18}O$ stable isotope values averaged −5.4‰ (−4.6‰ to −5.9‰) during the early site phase, −5.5‰ (−4.1‰ to −6.1‰) for the middle site phase, and −5.3‰ (−5.1‰ to −5.4‰) in the late site phase. These consistent values suggest a common geographic origin for the individuals we tested, most likely the Liangchengzhen area. Although the variation of $\delta^{18}O$ values that occurs in a population is not well established, the range of human $\delta^{18}O$ isotope values at Liangchengzhen is consonant with findings from other studies (Longinelli, 1984; White et al., 1998).

7. Discussion

7.1. Liangchengzhen isotope values

The results for faunal $\delta^{13}C$ isotope values at Liangchengzhen indicate that by the Longshan period domesticated animals were mainly fed millet, with more C_3 foods such as discarded portions of rice plants included by the later Longshan period as proposed by Yuan and Flad (2002). Average faunal apatite $\delta^{13}C$ isotope values at Liangchengzhen were more negative than faunal apatite $\delta^{13}C$ isotope values at other sites (Fig. 5).

The modern fish samples tested average about $\delta^{13}C$ −17.5‰, $\delta^{15}N$ 13.4‰, which is also more negative than commonly found for marine fish in other world regions. The solid surface residues from two middle phase *guan* jar pottery sherds excavated at the site produced $\delta^{13}C$ values averaging −18‰ and $\delta^{15}N$ values averaging +16‰, suggesting that both vessels contained fish (Tables 1 and 2, Fig. 5).

Overall, the $\delta^{13}C$ isotope values for human tooth enamel and apatite indicate a more C_3-based diet likely involving rice for most individuals in the Liangchengzhen sample and a C_4-based diet involving millet for only a few individuals (Fig. 4). Since rice and other C_3 plants average about −26‰, these results indicate that while some individuals consumed a significant amount of C_4 plants, or animals that ate C_4 plants, or marine foods in childhood, others had a diet high in C_3 foods. There is initial evidence for change in diet during the life time of individuals. Results from one individual (M50) indicated a difference in diet from childhood (2nd molar −9.5‰) to adulthood (−7.8‰, bone apatite), an increase in C_4 foods.

It would therefore appear that a significant amount of millet and/or domesticated animals fed millet was consumed, but even if fish were not important, millet and millet-fed animals comprised at most approximately 25–30% of the diet based on the average isotope value ($\delta^{13}C = -9.8$‰) of the 18 human samples tested at Liangchengzhen. Therefore, it is likely that aquatic resources were actually more important during the Longshan period at Liangchengzhen than what our preliminary results suggest. Unfortunately, without human collagen samples to provide nitrogen isotope results, we cannot estimate the relative contribution of aquatic or terrestrial foods to the diet of people at Liangchengzhen.

7.2. Theoretical issues

Social factors during the Longshan period may provide an explanation for the overall pattern of increased rice consumption at Liangchengzhen. During the Longshan, rice may have been grown primarily at large centers/sites in northern China. High seed

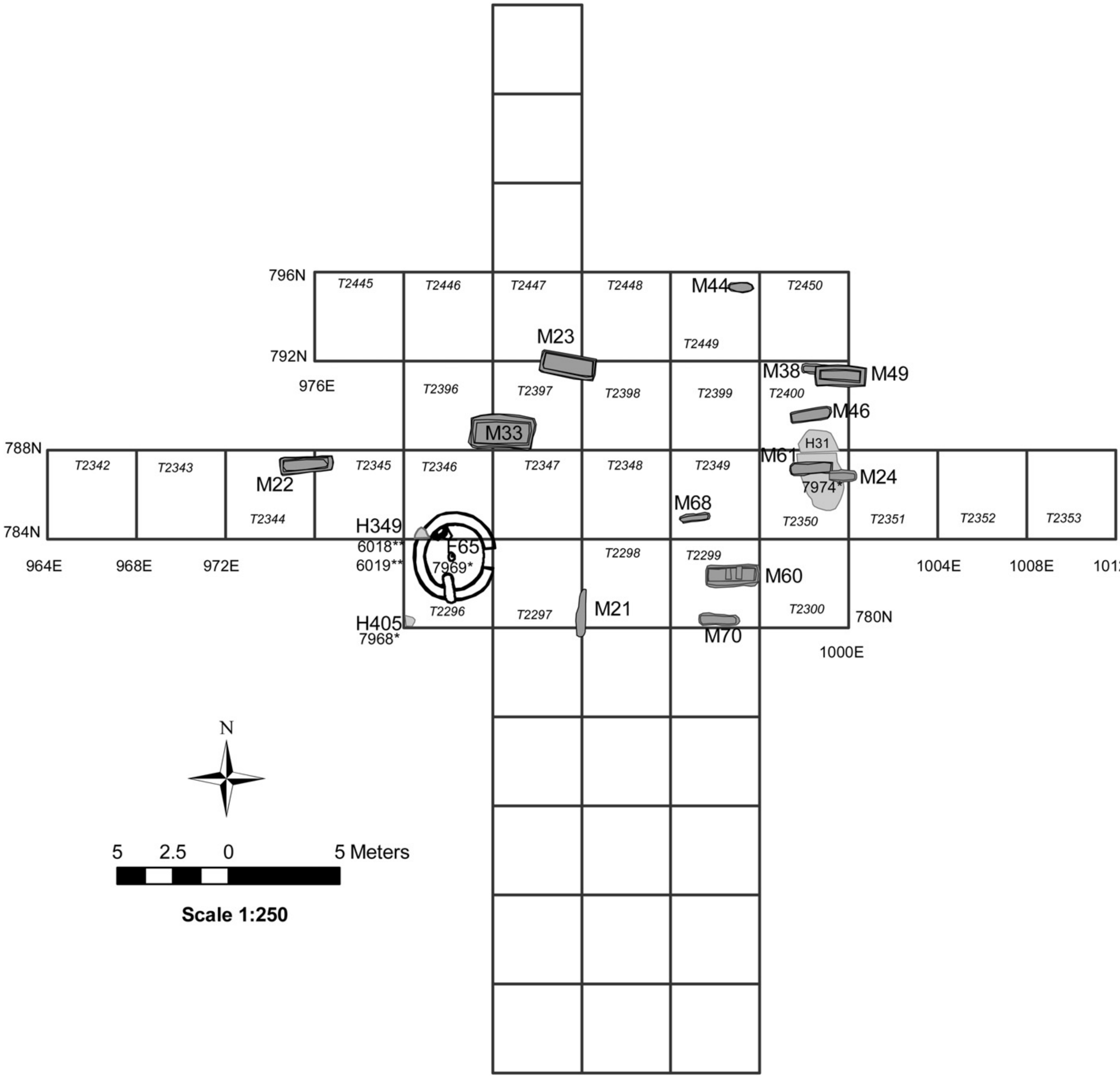

Fig. 3. Longshan period contexts for isotopic samples from the main excavation area at Liangchengzhen (* faunal sample; ** ceramic sample).

densities from other crop types were found at relatively small sites in the Yi-Luo survey area of Henan (Lee et al., 2007). Rice may have been cultivated at large centers such as Liangchengzhen as a preferred food and used for public ceremonies or as gifts to influence and acquire allies, a process proposed during the Shang period (see Underhill and Fang, 2004). A higher social status of some human consumers at Liangchengzhen, in comparison to residents of smaller settlements, could partially explain the pattern of greater availability of rice for ritual and other social contexts. Increased social stratification may have limited access to this preferred food at smaller sites (Underhill et al., 2008).

Rice has been identified from several contexts at Liangchengzhen as an ingredient for alcoholic beverages presumably used in feasting and ritual activities (McGovern et al., 2005a, 2005b). Chemical analysis of residues from ceramic vessels at Liangchengzhen excavated from the large, late phase pit H31, interpreted as used for ritual activities, revealed the presence of a fermented beverage made from rice in numerous samples (McGovern et al., 2005a, 2005b). We contend that this finding, along with the presence of some very large vessels, indicated that feasting for social and ritual purposes was an important part of life at the regional center of Liangchengzhen and supports ceremony and ritual as a use for rice (see also Underhill et al., 2008).

Feasting is evidenced at other Longshan sites in northern China, especially from high status burials (Underhill, 2002). The one faunal sample from the late phase at Liangchengzhen (#7974) indicating relatively more rice consumption was recovered from pit H31 containing over 200 nearly whole vessels. The remains in this pit likely resulted from ritual activities, perhaps offering sacrifices to ancestors as during later periods in northern China (Keightley, 1978;

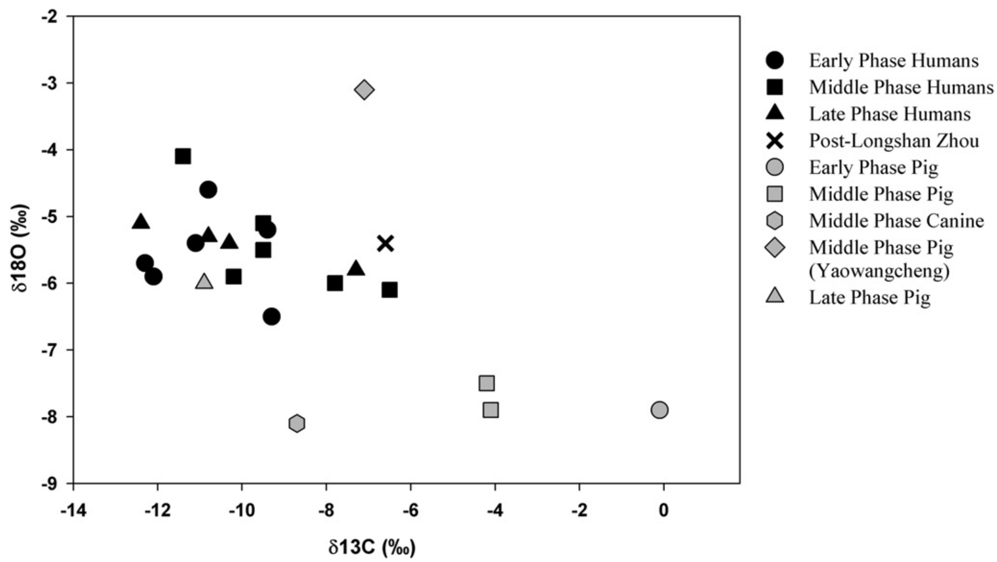

Fig. 4. $\delta^{13}C$ and $\delta^{18}O$ isotope values for human tooth enamel and apatite samples from Liangchengzhen, plus faunal samples from Liangchengzhen and Yaowangcheng.

Chang, 1980) and feasting. An animal in such a ritual pit may have been fed a diet with more rice than animals used for other purposes (Pechenkina et al., 2005). In addition, pig sample #7974 from late site phase pit H31 had an $\delta^{18}O$ value similar to human $\delta^{18}O$ values (Fig. 4). This may reflect a special dietary treatment, i.e., for ritual purposes, or using discarded plant portions for animal food.

Longinelli (1984) attributed a difference in $\delta^{18}O$ isotope values between domestic pigs and wild boars (spp. *Sus scrofa*) from the

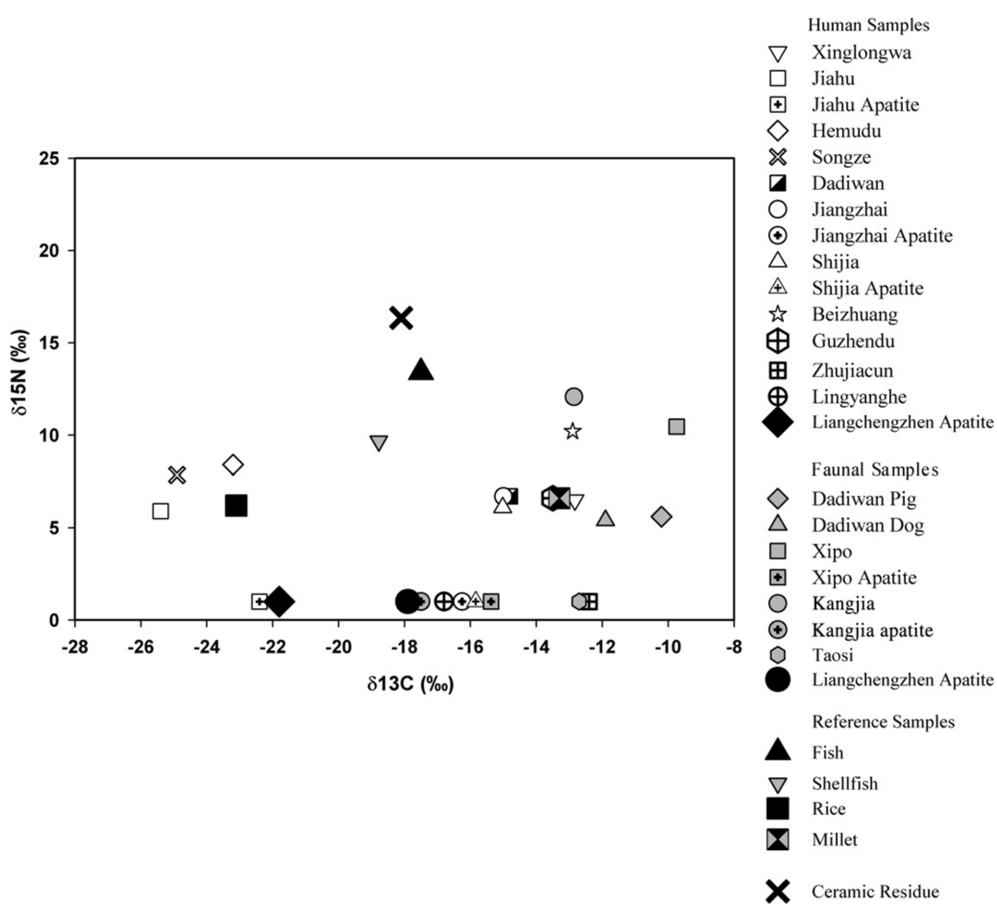

Fig. 5. Average estimated dietary values from bone collagen, bone apatite and tooth enamel, compared with food samples. The $\delta^{13}C$ isotope value for the modern rice sample has been adjusted by +1.5‰ to account for modern changes in atmospheric carbon. Human collagen values have been corrected to represent diet ($\delta^{13}C$ - 5‰, $\delta^{15}N$ - 3‰) and faunal collagen values have been corrected to represent flesh ($\delta^{13}C$ − 2‰, $\delta^{15}N$ - 3‰). Liangchengzhen apatite and tooth enamel values have also been corrected ($\delta^{13}C$ = − 12‰) to represent diet for humans and flesh for faunal samples, with $\delta^{15}N$ values arbitrarily assigned a value of 1‰ to show in this graph.

same locale to differences in the food supply. Although the samples in this study are from domesticated pigs, the difference in $\delta^{18}O$ isotope values for sample #7974 may be related to a differential dietary treatment.

Unfortunately, the small sample size for this study and the "apatite only" analysis of the $\delta^{13}C$ isotope values limit our ability at present to provide adequate data for interpretation of the diet-status relationship. Our hypotheses should be tested in the future with samples from other excavated Longshan sites in the Rizhao area. Early historic era India may provide a parallel case, where a pattern of rice becoming the preferred food by all households for social and ritual affairs in comparison to millet has been documented (Smith, 2006).

7.3. Isotope values at other Neolithic sites in China

In general, the isotopic data available from other Neolithic sites in China indicate a dietary dependence on C_4 foods such as millet during the early and middle Neolithic with isotope values becoming more negative by the late Neolithic (Figs. 1 and 5).

7.3.1. Early Neolithic

During the earlier Neolithic in northeast China, millet must have been the staple crop at the relatively early site of Xinglongwa (ca. 6000-4800 B.C.), in Inner Mongolia (see Shelach, 2000), with collagen $\delta^{13}C$ values around −7.6‰ and $\delta^{15}N$ = 9.5‰, suggesting that it comprised not only the dominant part of the whole diet but also perhaps half of dietary protein (Zhang et al., 2003). The average $\delta^{13}C$ collagen value (−7.9‰) from the Dawenkou period coastal site of Beizhuang (ca. 5000–3500 B.C.) also suggests a C_4 diet, but with a higher trophic level ($\delta^{15}N$ = 13.2‰).

In contrast, millet is not noticeable at the early Neolithic site of Jiahu (ca. 7000–5800 B.C.) in southern Henan province with average collagen and nitrogen values of $\delta^{13}C$ = −20.4‰, $\delta^{15}N$ = 7.9‰ indicating a C_3 diet, and average apatite values of $\delta^{13}C$ = −10.4‰ revealing a minor dietary component of millet (Hu et al., 2006). The Neolithic sites of Hemudu (ca. 5000–4500 B.C.) and Songze (ca. 3700–3300 B.C.) in the lower Yangzi River valley of southern China, where collagen $\delta^{13}C$ values averaged about −24‰ and $\delta^{15}N$ averaged about 8‰, also indicate a non-millet, C_3 diet (Zhang et al., 2003).

7.3.2. Middle Neolithic

During the middle Neolithic in north China, human collagen isotopic values from sites further west such as the Yangshao sites of Jiangzhai (ca. 4950–4050 B.C.), average value: $\delta^{13}C$ = −10.0‰, $\delta^{15}N$ = 8.8‰, and Shijia (ca. 4350–4050 B.C.), average value: $\delta^{13}C$ = −10.0‰, $\delta^{15}N$ = 8.1‰, in Shaanxi province indicate a dietary reliance on millet with only a small amount of consumption of animal protein (Pechenkina et al., 2005). Faunal values for pigs and dogs from Xipo, a late Yangshao site in Henan province, (average value: $\delta^{13}C$ = −7.7‰, $\delta^{15}N$ = 7.5‰, $\delta^{13}C_{apatite}$ = −3.4) also indicate a diet consisting primarily of millet (~90%) and low animal consumption (Pechenkina et al., 2005). Average collagen isotope values from late Dawenkou period sites Zhujiacun ($\delta^{13}C$ = −7.4‰), Lingyanghe (ca. 3500–2600 B.C.), $\delta^{13}C$ = −11.8‰, and Guzhendu, $\delta^{13}C$ = −8.5‰, $\delta^{15}N$ = 9.6‰ (ca. 3500-2600 B.C.) in Shandong province also reflect a large proportion of C_4 foods such as millet in the diet (Qi et al., 2004; Zhang et al., 2003).

C_4 foods were an important dietary staple during the late Yangshao phase at the site of Dadiwan in Gansu province (ca. 4550–2950 B.C.) as indicated by human (average value: $\delta^{13}C$ = −9.8‰, $\delta^{15}N$ = 9.7‰) and domesticated faunal (average value: $\delta^{13}C$ = −8.6‰, $\delta^{15}N$ = 8.6‰) collagen isotope values (Barton et al., 2009). The faunal isotope values at Dadiwan were high for both domesticated dogs (average value: $\delta^{13}C$ = −9.9‰, $\delta^{15}N$ = 8.4‰) and domesticated pigs (average value: $\delta^{13}C$ = −8.2‰, $\delta^{15}N$ = 8.6‰) indicating a reliance on millet or their incorporation into the human farming food web, especially dogs. Wild foraging pigs (average value: $\delta^{13}C$ = −18.1‰, $\delta^{15}N$ = 6.1‰) and free range pigs occasionally fed millet (average value: $\delta^{13}C$ = −15.1‰, $\delta^{15}N$ = 7.8‰) had lower isotope values.

7.3.3. Late Neolithic

During the late Neolithic in north China, average faunal values for domesticated pigs and dogs from Kangjia ($\delta^{13}C$ = −10.9‰, $\delta^{15}N$ = 9.1‰, $\delta^{13}C_{apatite}$ = −5.5), an early Longshan site (ca. 2500–2000 B.C.) in Shaanxi province, reflect less dependence on C4 foods (65–85%) and an increased trophic level (Pechenkina et al., 2005). The single collagen value, $\delta^{13}C$ = −10.7‰ from a pig at the Longshan site of Taosi also reflects less dependence on a C4 diet (Cai and Qiu, 1984).

8. Conclusions

The Liangchengzhen results indicate that by the Longshan period, people in southeastern Shandong no longer relied as heavily on millet, while it was probably a primary source of fodder for domesticated animals such as pigs and dogs. Fig. 5 reveals that Liangchengzhen apatite values ($\delta^{13}C$ = −9.8‰) were similar to apatite values at Jiahu ($\delta^{13}C$ = −10.4‰), a site known for rice cultivation. This suggests that other agricultural crops, especially rice, had increased in importance at Liangchengzhen. In general the pattern of a diverse agricultural system on the basis of the macrobotanical remains from Liangchengzhen (Crawford et al., 2004, 2005) is supported by the isotopic results. More thorough studies using larger samples of excavated remains in the Rizhao area of Shandong are needed to adequately test how diets changed during the Longshan period. The recovery of macrobotanical remains from other Longshan sites, and analyses of pottery residues and faunal remains will shed further light on variation in subsistence adaptations in northern China. In order to more adequately evaluate the hypothesis of stable dietary subsistence from the Longshan to the Zhou period, additional samples from early Bronze Age contexts in the Rizhao area are needed, including the Yueshi and Shang periods, estimated at ca. 1900–1100 B.C. (see Fang et al., 2008; Underhill et al., 2008).

This study illustrates the utility and advantages of investigating ancient diets by means of several methods. Further isotopic analysis of ceramic residues, now in progress, will provide important independent data from that of macrobotanical and faunal remains. Interpretations about diet require consideration of a range of archaeological materials from each period.

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