International Journal of Osteoarchaeology
Int. J. Osteoarchaeol. **28**: 85–94 (2018)
DOI: 10.1002/oa.2465

Diet Transition or Human Migration in the Chinese Neolithic? Dietary and Migration Evidence from the Stable Isotope Analysis of Humans and Animals from the Qinglongquan Site, China

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ABSTRACT The Qinglongquan site, China, includes materials from the Neolithic Qujialing (3000–2600 BC) and Shijiahe (2600–2200 BC) periods, and lies within the Sui-Zao Corridor that connects the Nanyang Basin in the north and the Hanjiang River Plain in the south. Previous research suggested a dietary shift from rice-based to millet-based agriculture between the Qujialing and Shijiehe periods at this site. The reason for this dietary shift is still unclear, and it is possible because of immigration into the region by people who already had a mainly C_4-millet-based diet (i.e. from Northern China). In this study, we examine the carbon (δ^{13}C) and nitrogen (δ^{15}N) results and present sulfur (δ^{34}S) isotope analyses of human ($n = 27$) and animal ($n = 36$) samples to test the hypothesis of whether this dietary shift was due to migration. The δ^{34}S values of the Qujialing humans ranged from 5.5‰ to 8.1‰ [average 6.5‰ ± 1.0 ($n = 7$)], and the δ^{34}S values of the Shijiahe humans ranged from 4.1‰ to 7.4‰ [average 5.8‰ ± 0.9 ($n = 18$)]. Because these values overlapped and were similar to the animal δ^{34}S results [4.3‰ to 8.8‰, average of 6.6 ± 1.3‰ ($n = 31$)], no evidence of migration was found for the humans with the different diets at the Qinglongquan site.

Key words: migration; stable isotope; the Qinglongquan site

Introduction

Although a dichotomy between the primitive rice agriculture in southern China and the primitive millet agriculture (foxtail millet and common millet) in Northern China during the Neolithic period is widely believed (Chen, 2005; Ren, 2005; Barton *et al.*, 2009; Zhao, 2011; Liu *et al.*, 2012), recent studies based on archaeological findings, archaeobotanical analysis and stable isotopic analysis have indicated that a mixed agricultural system of rice and millet was present from 5000 BC between the Yangtze River valley and the Yellow River valley (Hu *et al.*, 2006; Lanehart *et al.*, 2008; Fu *et al.*, 2010; Lanehart *et al.*, 2011; Guo *et al.*, 2011; Zhang *et al.*, 2014). This dynamic system was then more firmly established from 3500 to 2000 BC in the larger region including: Shandong, Henan, Hubei, Shaanxi, Anhui and Jiangsu Provinces. It has been

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Received 8 September 2014
Revised 12 April 2015
Accepted 10 May 2015

suggested that this combined rice and millet agriculture system played an important role in the formation of Chinese civilization (Zhao, 2011).

The Sui-Zao Corridor within the Hanjiang River valley (Figure 1) is widely believed to be an epicentre for cultural interaction between the Yangtze River valley and the Yellow River valley (Ren, 1989; Wang J., 1997; Su, 1999; Xu, 2003; Ma & Yang, 2007). The Qinglongquan site (Figure 1) is located in Yunxian County, Hubei Province and covers three different archaeological periods: the Yangshao Culture (3500–3000 BC), the Qujialing Culture (3000–2600 BC) and the Shijiahe Culture (2600–2200 BC). Large quantities of archaeological remains with different cultural styles were found, suggesting the frequent occurrence of cultural interaction (The Institute of Archaeology, Chinese Academy of Social Sciences, 1991; Chen *et al.*, 2010). In particular, the discovery of both rice and millet grains at the site implies that both crops were cultivated simultaneously (The Institute of Archaeology, Chinese Academy of Social Sciences, 1991). The rice-based Qujialing Culture, dominant in the middle Yangtze River region and famous for its unique ceramic balls and painted spindle whorls, expanded northwards around 3000 BC (Zheng, 1983; Fan, 1998; Sun, 2000; Meng, 2011) and controlled large areas in Northern China such as the Nanyang basin in Henan Province, Hubei Province, Hunan Province and some parts in Shaanxi Province (State Administration of Cultural Heritage, 1991; Fan, 2000). However, the situation was completely reversed during the Shijiahe period (2600–2200 BC). The Longshan Culture (3000–2000 BC) based on millet agriculture in the central plains along the middle and lower Yellow River valley began to move southwards and occupied the middle reach of the Yangtze River (Wang H., 1997), which was evidenced by the findings of large quantities of pottery with the surface ornamentation, colour and production technology of the Longshan Culture at the Qinglongquan site (Ma & Yang, 2007).

At this same time, the cultural transition between the rice-based and millet-based cultures was also reflected by the dietary change of human and animals through time. Our previous study (Guo *et al.*, 2011) at the Qinglongquan site showed that the carbon isotope values of humans (−15.7 ± 0.3‰, $n = 7$) and pigs (−15.5 ± 1.2‰, $n = 6$) during the Qujialing Culture period (3000–2600 BC) increased to −14.2 ± 0.3‰ ($n = 17$) and −13.2 ± 0.7‰ ($n = 5$), respectively, during the Shijiahe Culture period (2600–2200 BC). This isotopic variation of humans and pigs strongly indicates that the influence of the millet-based culture and dietary adaptations was enhanced through time because of the strong influence of the Longshan Culture (Guo *et al.*, 2011). However, this dietary change of the humans could also be caused by the movement of humans from the north (who already had a millet-based

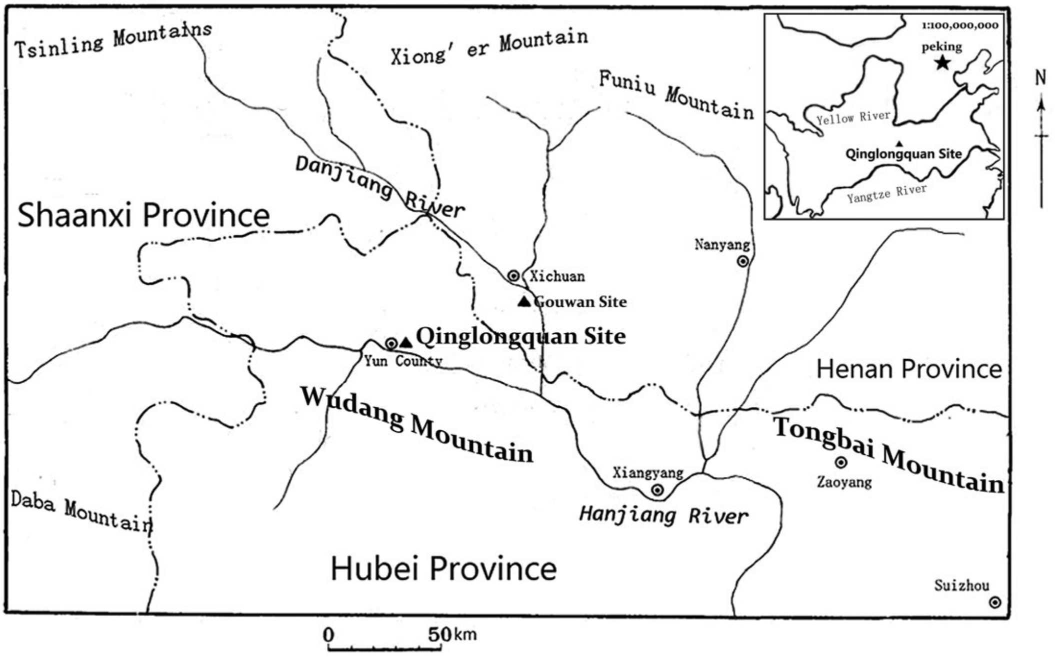

Figure 1. Site map of the Qinglongquan site.

economy) to this site (The Henan Provincial Institute Archaeology, The Henan Group of The Archaeological Team, 1972; The Henan Provincial Institute Archaeology, The Henan Group of The Archaeological Team, 1989; Zhou, 1992; Li, 2000; Guo, 2004). To test this hypothesis, we analysed additional human and animal samples from the Qinglongquan site, and in particular, we employed sulfur isotopic analysis, as it has been shown to be a potential indicator of human migration (e.g. Nehlich *et al.*, 2012; Nehlich, 2015).

Stable carbon, nitrogen and sulfur isotope analysis

Carbon and nitrogen stable isotope analysis of human and animal bone collagen from archaeological sites has become an established method to reconstruct past diets in China (e.g. Zhang *et al.*, 2003; Pechenkina *et al.*, 2005; Hu *et al.*, 2009a; Guo *et al.*, 2011). The technique and different applications are well described in numerous publications (e.g. DeNiro & Epstein, 1978; van der Merwe & Vogel, 1978; DeNiro, 1985; Larsen, 1997; Richards, 2002; Choy *et al.*, 2010; Nehlich *et al.*, 2012; Quintelier *et al.*, 2014; Schoeninger, 2014), and the topic has been reviewed in detail by Lee-Thorp (2008). In general, carbon isotope values can clearly distinguish the consumption between C_4 and C_3 diets (Webb *et al.*, 2013; Hou *et al.*, 2013). In China, the carbon isotope values of humans and animals can be used to evaluate the consumption of C_3 rice-based foods and C_4 millet-based foods (Hu *et al.*, 2007; Barton *et al.*, 2009; Lanehart *et al.*, 2011). Nitrogen isotopic values in collagen increase by 3–5‰ with increasing trophic level, and this is quite useful for differentiating between animal-based and plant-based diets as well as the consumption of the terrestrial foods from aquatic ecosystems (freshwater or marine) (Ambrose, 1991; Arcagni *et al.*, 2013). Unlike carbon and nitrogen, the use of sulfur stable isotope analysis in bone (and dentine) collagen has only been developed in recent years because of the advancement in the ability to measuring the sulfur isotope values in collagen using isotope ratio mass spectrometer (Richards *et al.*, 2001; Hedges *et al.*, 2005; Craig *et al.*, 2006; Privat *et al.*, 2007; Pellegrini & Longinelli, 2008; Fornander *et al.*, 2008).

Plants receive sulfate not only from the weathering of local bedrock through their roots but also from the atmosphere, from droplets from sea evaporation or from precipitation containing dissolved sulfur gases (H_2SO_4, H_2S and SO_2). In areas where these various sulfur sources have significantly different isotope sources, the uptake of sulfur by plants will be an average of the individual sources (Linderholm & Kjellström, 2011). It has been demonstrated that fractionation of sulfur isotopes within plant ecosystems is small, with $\delta^{34}S$ values typically 1.5‰ lower than environmental sulfate (Krouse, 1977; Winner *et al.*, 1978; Case & Krouse, 1980). Feeding experiments show that for an adequate protein C_3 diet, the $\delta^{34}S$ values in herbivorous mammals were shifted by −1‰ (Richards *et al.*, 2003a). The range of sulfur isotope values in terrestrial ecosystems is relatively large (−10‰ to +20‰) and even wider in freshwater system (−22‰ to +20‰) because of the action of anaerobic bacteria in the sediments of rivers and lakes (Linderholm & Kjellström, 2011), and the mean sulfur isotope ratio of oceanic seawater sulfate is +20.3‰ (Nehlich, 2015). Thus, sulfur isotope analysis can have the advantage of being able to differentiate between the consumption of terrestrial and aquatic (marine or freshwater) resources by humans or animals (Hu *et al.*, 2009b; Nehlich, 2015).

Sulfur isotope analysis also holds potential to investigate human residence and mobility. Because of the direct input of sulfur with local bedrock to bone collagen and its relatively low turnover rate (≥10 years, depending on the bone element sampled), the variation of $\delta^{34}S$ values among humans can be discerned if significant differences exist in local geology between the birth location and the later residence location (Bol & Pflieger, 2002; Vika, 2009). For these studies, the $\delta^{34}S$ values of animals are used to determine the local isotopic baseline $\delta^{34}S$ values.

Materials and methods

In total, 31 human remains as well as 53 animal bones were selected for stable isotope analysis (Table 1), some of which had already been reported in the previous study (Guo *et al.*, 2011). One sample was taken from each human skeleton, and in sample selection, preference was given to the femur.

Bone collagen was extracted following the procedures described by Richards & Hedges (1999) with the addition of an ultrafiltration step (Brown *et al.*, 1988). Approximately 300–500 mg of bone was sampled and the surface contaminants were removed mechanically. The bone samples were demineralized in 0.5 M HCl at 5 °C and refreshed every 2 or 3 days until the bone samples were demineralized. Then, the samples were rinsed in deionized water three times and gelatinized at 70 °C in 0.001 M HCl for 48 h. After that, the resulting solution was first filtered to remove insoluble materials and then filtered again to remove

Table 1. Information on the bone samples and isotopic data

Sample ID	Description	Culture period	Collage*n* (%)	C (%)	N (%)	S (%)	δ^{13}C (‰)	δ^{15}N (‰)	δ^{34}S (‰)	C : N	C : S	N : S
M155*	Human	Qujialing culture	3.5	44.5	16.3	0.2	−15.3	9.9	6.5	3.2	628.1	197.5
M190*	Human	Qujialing culture	4.6	43.8	16.5	0.2	−15.9	9.2	5.5	3.1	635.2	205.3
M157E*	Human	Qujialing culture	2.2	44.0	16.6	0.2	−16.5	10.1	7.0	3.1	613.8	199.0
M79*	Human	Qujialing culture	5.4	44.6	17.0	0.2	−14.1	6.8	5.5	3.1	625.3	204.0
M184*	Human	Qujialing culture	2.0	43.9	16.2	0.2	−16.1	9.2	8.1	3.2	533.1	169.2
M157W*	Human	Qujialing culture	6.2	44.6	16.8	0.2	−15.5	9.8	5.7	3.1	757.2	244.9
M162*	Human	Qujialing culture	2.2	43.9	15.8	0.2	−16.7	9.9	7.0	3.2	547.4	169.0
M160	Human	Qujialing culture	NA									
M132*	Human	Shijiahe culture	4.5	44.8	16.6	0.2	−12.9	8.5	6.6	3.2	625.9	198.7
M69*	Human	Shijiahe culture	0.9	44.6	16.6	0.2	−12.4	9.9	5.5	3.1	672.4	214.9
M110A*	Human	Shijiahe culture	5.4	45.1	16.4	0.2	−13.1	9.2	5.8	3.2	575.8	179.0
M78*	Human	Shijiahe culture	3.9	44.7	16.9	0.2	−14.7	8.2	6.0	3.1	624.2	202.5
M67*	Human	Shijiahe culture	3.0	43.9	15.8	0.2	−12.9	9.4	5.2	3.3	577.1	177.9
M127*	Human	Shijiahe culture	1.4	43.9	15.5	0.2	−13.7	8.2	NA	3.3	NA	NA
M187*	Human	Shijiahe culture	3.6	44.0	15.9	0.2	−15.3	9.2	7.4	3.2	596.1	184.9
M110B*	Human	Shijiahe culture	0.3	44.0	16.7	0.2	−14.2	9.6	6.5	3.1	630.8	205.5
M133*	Human	Shijiahe culture	3.7	42.9	15.1	0.2	−14.6	6.6	4.1	3.3	575.4	173.2
M139*	Human	Shijiahe culture	2.2	43.6	16.0	0.2	−15.4	9.7	6.6	3.2	635.5	199.6
M128*	Human	Shijiahe culture	4.0	43.9	16.6	0.2	−13.6	8.9	5.2	3.1	628.8	204.4
M145*	Human	Shijiahe culture	4.5	43.6	16.6	0.2	−15.9	10.8	4.7	3.1	653.0	212.6
M158*	Human	Shijiahe culture	5.1	44.5	16.8	0.2	−14.0	9.5	6.9	3.1	595.8	193.4
M124*	Human	Shijiahe culture	3.1	43.6	16.2	0.2	−14.3	6.7	5.1	3.1	645.5	205.3
M118*	Human	Shijiahe culture	1.8	44.4	16.1	0.2	−15.7	9.2	6.9	3.2	713.7	221.1
M98*	Human	Shijiahe culture	1.6	44.0	15.9	0.2	−15.4	7.1	5.9	3.2	570.1	176.0
M148*	Human	Shijiahe culture	0.4	45.4	17.0	0.2	−13.0	10.4	6.2	3.1	579.1	186.0
M107	Human	Shijiahe culture	NA									
M42	Human	Shijiahe culture	NA									
M40	Human	Shijiahe culture	NA									
M172	Human	Shijiahe culture	1.0	43.5	15.7	*0.8*	−12.7	9.6	*6.3*	3.2	*140.2*	*43.3*
M189	Human	Shijiahe culture	4.1	43.6	15.9	0.2	−13.9	8.4	5.6	3.2	509.8	159.1
TN1E2(2):19	Human	Shijiahe culture	3.1	43.4	15.7	0.2	−17.6	8.7	4.2	3.2	625.0	193.6
TN1W2(10):25	Pig	Yangshao culture	0.7	42.6	15.3	0.2	−17.2	7.1	4.3	3.3	719.7	221.3
TN1E1(10):8	Pig	Yangshao culture	3.3	43.8	15.3	0.2	−19.9	3.9	5.9	3.4	580.8	173.5
TN1W2(9):27	Pig	Yangshao culture	0.8	44.0	14.9	NA	−19.0	5.3	NA	3.4	NA	NA
M162*	Pig	Qujialing culture	0.9	43.3	15.4	0.2	−20.8	8.9	6.5	3.3	594.6	181.4
H478*	Pig	Qujialing culture	1.7	44.4	15.3	0.2	−17.5	7.8	7.4	3.4	629.5	186.5
H667*	Pig	Qujialing culture	2.7	44.6	16.1	0.2	−17.4	7.8	7.5	3.2	588.9	182.6
H163B*	Pig	Qujialing culture	0.9	43.7	16.3	NA	−13.9	7.4	NA	3.1	NA	NA
H463A*	Pig	Qujialing culture	3.8	44.3	15.6	0.2	−13.9	7.1	7.1	3.3	637.8	192.7
H595*	Pig	Qujialing culture	2.3	44.5	16.0	0.2	−13.4	7.9	7.6	3.3	534.7	164.8
H463B*	Pig	Qujialing culture	3.8	44.6	16.5	0.2	−11.7	7.5	8.2	3.2	508.6	161.2
TN1E1(6):4	Pig	Qujialing culture	3.2	43.4	15.7	0.2	−16.9	5.4	6.8	3.2	561.3	173.9
TN1W1(5):11	Pig	Qujialing culture	0.8	43.1	15.6	NA	−17.7	7.1	NA	3.2	NA	NA
TN1W2(7):23	Pig	Qujialing culture	3.6	42.7	15.5	0.2	−19.9	3.5	5.6	3.2	546.9	170.2
TN1W2(8):26	Pig	Qujialing culture	0.7	42.9	15.0	0.2	−14.1	5.6	6.0	3.3	517.8	155.4
TN1W2(6):24	Pig	Qujialing culture	1.4	43.0	15.7	0.2	−21.7	4.5	6.9	3.2	561.4	175.9
TN1E2(6):18	Pig	Qujialing culture	3.2	42.9	15.7	0.2	−18.7	4.4	6.2	3.2	574.6	179.9
TN1E1(5):2	Pig	Qujialing culture	0.2	45.1	13.8	NA	−17.4	*6.5*	NA	3.9	NA	NA
TN1E1(7):3	Pig	Qujialing culture	0.9	43.3	15.3	0.2	−14.6	6.1	6.8	3.3	510.7	154.2
TN1E1(4):5	Pig	Qujialing culture	0.3	43.0	14.9	0.2	−21.1	4.0	4.5	3.4	687.3	203.4
H597	Pig	Qujialing culture	NA									
H131	Pig	Qujialing culture	NA									
H163A	Pig	Qujialing culture	NA									
H367	Pig	Qujialing culture	NA									
M155A	Pig	Qujialing culture	NA									
M155B	Pig	Qujialing culture	NA									
M148B*	Pig	Shijiahe culture	0.3	43.3	15.2	NA	−12.0	7.6	NA	3.3	NA	NA
H590*	Pig	Shijiahe culture	1.6	44.1	15.4	0.2	−13.7	6.1	5.8	3.3	515.1	154.7
H576*	Pig	Shijiahe culture	2.9	44.4	16.1	0.3	−16.3	4.7	8.0	3.2	416.9	129.2
H579*	Pig	Shijiahe culture	2.0	43.8	15.2	0.2	−13.0	8.0	8.2	3.4	486.3	144.9
H546B*	Pig	Shijiahe culture	2.3	44.6	16.2	0.3	−11.0	8.3	7.4	3.2	459.5	142.9
H578*	Pig	Shijiahe culture	3.0	44.6	15.8	0.2	−13.2	8.2	8.1	3.3	565.7	171.4
TN1E1(2):7	Pig	Shijiahe culture	3.5	43.3	15.4	0.2	−12.2	6.1	7.1	3.3	598.8	182.4

(*Continues*)

Table 1. (Continued)

Sample ID	Description	Culture period	Collagen (%)	C (%)	N (%)	S (%)	δ^{13}C (‰)	δ^{15}N (‰)	δ^{34}S (‰)	C : N	C : S	N : S
TN1W1(3):10	Pig	Shijiahe culture	2.7	43.6	15.3	0.2	−20.5	3.9	6.4	3.3	492.7	147.8
M141	Pig	Shijiahe culture	NA									
H634	Pig	Shijiahe culture	NA									
H546A	Pig	Shijiahe culture	NA									
M127	Pig	Shijiahe culture	NA									
M135	Pig	Shijiahe culture	NA									
M148A	Suidae	Shijiahe culture	NA									
TN1W2(5):22	Sheep/Goat	Qujialing culture	1.1	43.0	15.6	0.2	−21.5	3.9	3.3	3.2	593.4	185.0
H163C	Dog	Qujialing culture	NA									
H28	Dog	Shijiahe culture	3.5	44.2	15.4	0.2	−19.1	6.5	6.9	3.4	499.7	149.0
TN1E2(10):21	Deer	Yangshao culture	NA									
TN1W1(6):12	Deer	Qujialing culture	NA									
TN1W1:2	Deer	Shijiahe culture	1.0	43.2	15.4	0.2	−19.5	3.8	5.9	3.3	576.0	176.5
TN1W1(7):13	Unidentified animal	Yangshao culture	1.1	43.1	15.7	0.2	−21.3	4.9	4.7	3.2	555.0	172.9
TN1E2(11):16	Unidentified animal	Yangshao culture	3.4	43.4	15.5	0.2	−13.1	6.1	6.4	3.3	486.5	149.0
TN1E1(8):6	Unidentified animal	Yangshao culture	1.6	43.8	15.1	0.3	−14.3	6.4	8.8	3.4	431.4	127.0
TN1E2(9):15	Unidentified animal	Yangshao culture	2.2	42.1	15.0	0.2	−21.7	4.5	7.9	3.3	480.2	146.8
TN1E1(9):9	Unidentified animal	Yangshao culture	2.2	43.7	15.0	0.2	−16.1	6.0	7.4	3.4	496.3	146.1
TN1E2(8):20	Unidentified animal	Qujialing culture	2.8	43.4	15.6	0.2	−15.1	4.1	7.5	3.2	525.9	162.1
TN1E2(5):14	Unidentified animal	Qujialing culture	NA									
TN1E2(3):17	Unidentified animal	Shijiahe culture	3.1	43.0	15.7	0.2	−17.4	7.0	4.8	3.2	556.8	173.9

NA, not applicable.
*The δ^{13}C and δ^{15}N values of these samples are published in 2011.

contaminants <30 kDa by using Millipore Amicon Ultra-4 centrifugal filters. Finally, the residues were freeze-dried for 48 h. After the extracted collagen was weighed, the collagen content ratio was calculated (the weight of the collagen was divided by the original weight of the bone sample).

Approximately 0.5-mg collagen was analysed for carbon and nitrogen isotopic measurements. Samples were combusted and analysed in a Flash EA 1112 coupled to a Delta XP (Thermo-Finnigan). Approximately 10 mg of bone collagen was weighed out and mixed with 1 mg of V_2O_5 to catalyse the combustion and reduce variability (Nehlich *et al.*, 2011). The material was then combusted in a Heka EuroVector elemental analyser (HeKaTech) and analysed in a Thermo-Finnigan Delta V plus. Stable isotope ratios are expressed relative to the VPDB (C), AIR (N) and VCDT (S), respectively. Measurement errors on the δ^{13}C and δ^{15}N are ±0.2‰, and ±0.5‰ for the δ^{34}S measurements, respectively. The isotopic data, collagen quality indicators, and some information on the samples individuals were listed in Table 1 for both human and animal bones.

Results and discussion

Bone collagen preservation

Except for four samples (M160, M107, M42 and M40), the humans ($n = 27$) had atomic C : N ratios within the acceptable range from 2.9 to 3.6 (DeNiro, 1985; van Klinken, 1999). Four contained low collagen by weight (<1%), which indicated that the majority of bone collagen had decomposed during burial. There were also 36 acceptable samples out of 53 animal bone samples in total. The sulfur content of the human and animal bone collagen met the accepted range between 0.15% and 0.35% (Nehlich & Richards, 2009) except for the M172 human sample. The atomic C : S and atomic N : S ratios also met the quality criteria of 600 ± 300 and 200 ± 100, respectively, except for M172 (Nehlich & Richards, 2009).

Carbon and nitrogen isotope analysis of humans and animals from the Qinglongquan site

The δ^{13}C and δ^{15}N values of all samples from the Qinglongquan site are plotted in Figure 2. The herbivores, including one sheep/goat and one deer, have a mean δ^{15}N value of 3.9 ± 0.1‰ as expected for herbivores from this temperate inland region (Richards & Hedges, 2003b). Their mean δ^{13}C value (−20.5 ± 1.4‰, $n = 2$) suggests that C_3 plants generally dominated their diets. Seven unidentified mammals, likely herbivores have a large range of δ^{13}C values from −21.7‰ to −13.1‰ with the mean value of −17.0 ± 1.3‰, suggesting that they have quite different diet resources including both C_3 and C_4 deprived foods. Their δ^{15}N data are from 4.1‰ to 7.0‰ with

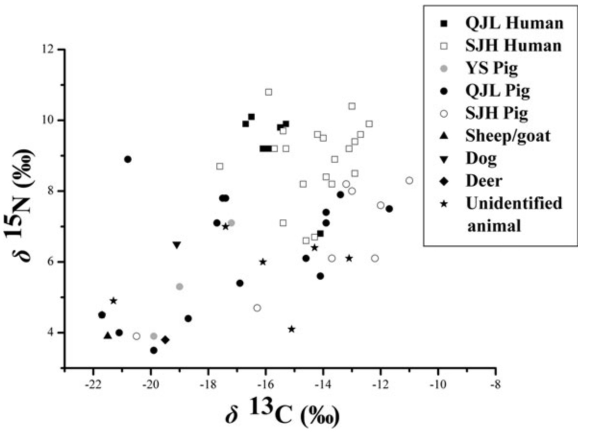

Figure 2. Plot of δ^{13}C and δ^{15}N values of bone collagen of humans and animals. QJL, Qujialing; SJH, Shijiahe; YS, Yangshao.

the mean value of 5.6 ± 0.4‰, located in the expected range for herbivores.

The δ^{13}C value of a single dog is −19.1‰, indicating the major input was C_3 foods. Its δ^{15}N value (6.5‰) is 2.7‰ more enriched than the mean value of herbivores, suggesting this dog might have had a large amount of animal protein as expected for an omnivore (DeNiro & Epstein, 1978; Hedges & Reynard, 2007).

The δ^{13}C values of pigs range widely from −11.0‰ to −21.7‰ (Table 1, Figure 2) suggesting the consumption of both C_3-based and C_4-based foods. The mean δ^{13}C values (−16.2 ± 3.3‰, $n = 26$) of the pigs are significantly ^{13}C-enriched compared with other animals including deer, sheep/goat and dog (independent t-test, $t = 3.88$, $p = 0.008 < 0.05$), which may relate to human intervention in their feeding strategy with the use of C_4 plants (Hu *et al.*, 2009a). A relatively wide range (5.4‰) of δ^{15}N values is seen in the pigs. The large variation in pig δ^{13}C and δ^{15}N values may be interpreted as the disproportional consumption of C_4-based foods (Chen *et al.*, 2012) or the coexistence of wild boars and domestic pigs in this site (Luo *et al.*, 2009), which will be discussed further. The exception is sample M162, with the highest δ^{15}N value (8.9‰) and extremely low δ^{13}C value (−20.8‰), strongly implying that this specimen might have a different feeding strategy or was not local. More detailed analysis of this sample combined with sulfur isotope analysis will be discussed in the succeeding text.

Many of the human carbon and nitrogen data were previously published by Guo *et al.* (2011), and demonstrated that the diet was a mix of C_3 and C_4 foods. The additional humans presented here in this study also have this pattern.

Sulfur isotope analysis

In general, the sulfur isotope values of the terrestrial animals, including pig, dog, deer, sheep/goat and unidentified animals, have δ^{34}S values ranging from 3.3‰ to 8.8‰, with an average of 6.6 ± 1.3‰ ($n = 32$) (Table 1; Figure 3). However, there is substantial isotopic variation among the species. The average δ^{34}S value of the herbivores is 4.6 ± 1.8‰ ($n = 2$) whilst that of the pigs is higher [6.7 ± 1.1‰; ($n = 22$)]. The δ^{34}S value of the single sheep/goat (3.3‰) is considerably different from the other fauna, and we have excluded it from the herbivore δ^{34}S isotopic baseline in the following discussions. Although the animals date to three cultural periods, no significant difference in δ^{34}S values among animals through time was observed (K independent samples test, $p = 0.832 > 0.05$). This relatively small isotopic variance of these terrestrial animals creates a good opportunity for us to set up the local isotope baseline, aiming to differentiate human movements.

The range of human δ^{34}S values is between 4.1‰ and 8.1‰ with an average of 6.0‰ ± 1.0 ($n = 25$) (Table 1; Figure 3). It is depleted by an average of 0.7‰, compared with that of the terrestrial animals (6.7 ± 0.2‰, $n = 31$). Considering that the fractionation of sulfur isotopes between trophic levels is ≈−1‰ (McCutchan *et al.*, 2003), we confirm that these herbivores played a key role in human diet at this site.

The small range of human sulfur isotopic data also reveals no significant consumption of freshwater fish (also indicated by the δ^{15}N values). However, without δ^{34}S values of local freshwater fish, we cannot confirm this, and it is also plausible that no significant difference of δ^{34}S values between human individuals would be expected, because there might be considerable over-

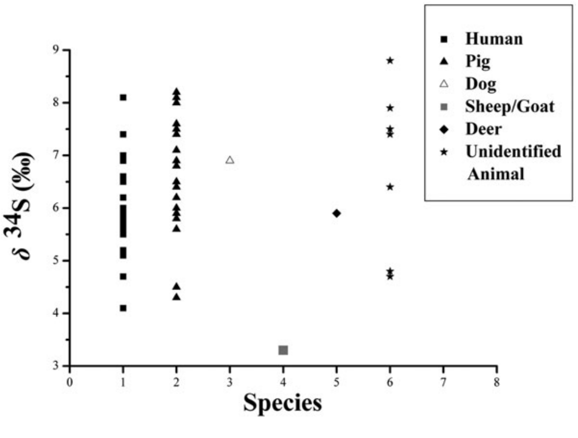

Figure 3. Plot of δ^{34}S values of humans and animals from the Qinglongquan site.

lap between the $\delta^{34}S$ ranges of fish and terrestrial animals (Privat *et al.*, 2007; Nehlich *et al.*, 2010).

The $\delta^{34}S$ value of the M162 pig sample that has different carbon (−20.8‰) and nitrogen (8.9‰) isotope values is similar to the other pigs at the Qinglongquan site. This result indicates that this pig was not a migrant but that it had a very different diet compared with the other pigs at the site. One possible reason for this is that this M162 pig was reared on a unique diet specifically for ritual sacrifice (Craig *et al.*, 2010; Chen *et al.*, 2012).

Change of human and animal sulfur values between periods

In our previous study (Guo *et al.*, 2011), dietary shifts of both humans and pigs to C_4-based foods were found at the Qinglongquan site between the Qujialing to Shijiahe periods. This diet shift was accounted for by the movement southwards by millet-based northern Longshan Culture (Guo *et al.*, 2011). Did a potential human migration also occur during this cultural interaction? If we compare the sulfur isotope values of local animals as a reference to the human values in different periods, it can give us more clues about possible human migration at the Qinglongquan site.

Because all of the animals measured for $\delta^{34}S$ in this study could all have contributed to human diet as discussed previously, their $\delta^{34}S$ values can be used as local geological signals. The values of all animals range from 4.3‰ to 8.8‰, averaging 6.7 ± 1.2‰ ($n = 31$) (Table 1, Figure 4). Because there is no significant difference of animal sulfur isotope data between the Qujialing and Shijiahe periods ($t = 0.241$, $p = 0.812 > 0.05$), although the pigs obtained more millet, the sulfur values of all the aforementioned animals are used here to set up the local baseline to understand the human movements in different periods.

The sulfur values of the Qujialing humans range from 5.5‰ to 8.1‰, averaging 6.5‰ ± 1.0 ($n = 7$) (Table 1, Figure 4). Based on an independent t-test, there is no significant difference between the Qujialing human and local animals ($t = -0.544$, $p = 0.590 > 0.05$), which indicates that most Qujialing humans were locals. The values of the Shijiahe humans range from 4.1‰ to 7.4‰, averaging 5.8‰ ± 0.9 ($n = 18$) (Table 1, Figure 4). Although the mean $\delta^{34}S$ value of the Shijiahe humans is lower than those of the Qujialing humans and the local animals and shows significant difference from the local animals by statistical analysis (independent t-test, $t = -2.888$, $p = 0.006 < 0.05$), the differences are actually less than 1‰ and too small to result from migration. Furthermore, an independent t-test shows no difference between the Qujialing and the Shijiahe human $\delta^{34}S$ values ($t = 1.591$, $p = 0.125 > 0.05$), which also suggests that the Shijiahe humans were not immigrants. Although the archaeological evidence suggests cultural interactions were occurring between northern and southern Neolithic cultures during the Shijiahe period at the Qinglongquan site, our isotopic results do not support the migration hypothesis at this time. Thus, this mixing of cultural characteristic might have been the result of trade or the transmission of ideas, or it is possible that migration was indeed occurring but that we were not able to detect it with this form of $\delta^{34}S$ analysis.

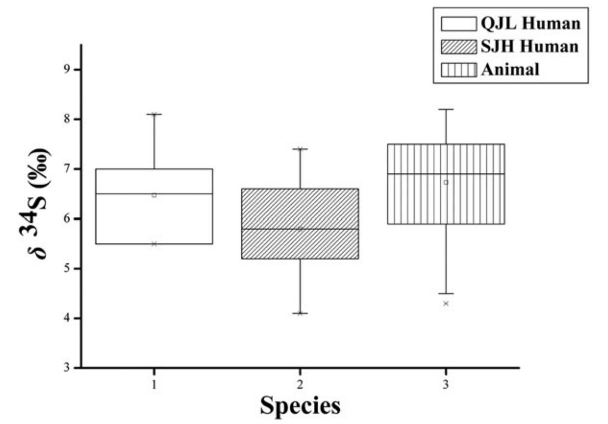

Figure 4. Box plots of the sulfur isotope values of animals and humans from the two time periods. QJL, Qujialing; SJH, Shijiahe.

Relationship between diet variation and human migration

Increasingly, research suggests that human diet varied to some extent during the Chinese Neolithic. At sites like Guowan and Liangchenzhen, rice was found to be an increasingly important part of the diet (Lanehart *et al.*, 2008; Fu *et al.*, 2010; Lanehart *et al.*, 2011). However, many questions still remain about this period. What events and factors triggered these radical shifts in diet and were they related to human movements at the sites? Additional research aimed at exploring these questions will provide a better understanding of dietary variation, cultural development and interactions and lead to a clearer picture of the foundation of Chinese civilization. Unfortunately, the study of human migration and how it influences cultural transition in Neolithic China is rarely systematically studied. We hope that the results presented here will encourage more research using sulfur and strontium stable isotope ratios in bones and teeth to detect migration patterns in archaeological sites from across China.

Conclusions

Carbon, nitrogen and sulfur isotope analysis of humans and associated animals from the Qinglongquan site indicates that the humans most likely obtained a substantial portion of their protein from a terrestrial ecosystem. No large differences are found among the humans from the two time periods and the local animal sulfur values at this site suggesting that the human populations were probably not migrants to the site. Whilst we did not identify typical migrants, this study enhances our understanding of the social and dietary complexity during the late Neolithic period. Finally, we hope that this research will spur additional studies using sulfur isotope at sites across China in order to better understand the relationships between human diet and cultural interactions during the Neolithic.

Acknowledgements

We want to thank two anonymous reviewers for their critical reading of the paper that greatly improved our manuscript, as well as Ben Fuller for his comments and help with the revision of the manuscript. This work was supported by the Max-Planck Society, National Natural Science Foundation of China (Grant No. 41102014), Scientific Research Fund of Zhejiang Provincial Education Department (Grant No. Y201225579), Qianjiang Talents Program of Zhejiang Province (Grant No. QJC1202009), Zhijiang Junior Social Scientists Program of Zhejiang Province and the Fundamental Research Funds for the Central Universities.

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