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ORIGINAL PAPER

A multi-isotope analysis on human and pig tooth enamel from prehistoric Sichuan, China, and its archaeological implications

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Abstract

In this study, we conducted carbon, strontium, and oxygen isotope analyses on tooth enamel from human and pig remains that were excavated from the Chengdu Plain and its western highlands in Sichuan to investigate the dietary patterns of the peoples and possible population movements in these areas. The analyses of carbon isotope showed that the dietary patterns in these areas support our previous understanding that, while rice was an important food source for the peoples on the Chengdu Plain, millets played a crucial role at the mountainous sites. Moreover, the same dietary patterns in these two regions lasted from the late Neolithic Age to at least the Bronze Age. The result of strontium analyses suggests that the bioavailable strontium baseline of the Chengdu Plain is 0.71197–0.71400. Based on this strontium ratio and $\delta^{13}C$ value ranges derived in this study, several unusual cases were identified. We also note an interesting difference in the oxygen isotope values between the late Neolithic and the early Bronze Age sites, which we suspect to be related to climate change in around 2000 BC. This finding, however, requires more data for verification. Overall, this is the first time isotopic analysis was used to test human and faunal remains in a more extensive manner and to enhance our understanding of the paleodietary patterns, human dynamics, and climatic changes in ancient Sichuan. The results provide information about the sites when other sources of evidence are lacking and suggest a baseline for future comparisons.

Keywords Chengdu Plain · Sichuan highlands · Multi-isotopic analysis · Migration · Paleodiet

Introduction

The Chengdu Plain of the Upper Yangzi River and its western highlands (Figure 1) were important regions in ancient times where human groups, artifacts, knowledge, and innovative ideas spread rapidly. Such material and cultural exchanges, along with a considerable amount of communication among the regional cultures, have been evidenced by archaeological studies. For example, painted pottery of the northern styles was found in the western Sichuan highlands, mainly along the Upper Min River and Dadu River during the Yingpanshan Period (ca. 3300–2700 BC) (e.g., Chen et al. 2004; Sichuan et al. 2007; Chengdu et al. 2007, 2010, 2018; Aba et al. 2008). Under the same cultural influence of the north, millet agriculture was also adopted by the inhabitants of the Upper Min River at about 3500–3300 BC (d'Alpoim Guedes 2011; Huo 2009; Zhao and Chen 2011). Later, millet appeared on the Chengdu Plain at about 3000 BC (d'Alpoim Guedes and Wan 2015; Huo 2009; Wan and Lei 2013) and in the valleys of the Yalong River to the southwest between 2800 and 2300 BC (Chengdu et al. 2016c).

The Baodun Culture (ca. 2500–1700 BC) represents the first full-fledged Neolithic culture on the Chengdu Plain, during which rice had replaced millet as the most important grain (Chengdu and Xinjin 2011; d'Alpoim Guedes 2011; d'Alpoim Guedes et al. 2013) and pigs were the most important protein sources (He et al. 2020). This newly developed subsistence was very likely introduced from the Middle Yangzi River (d'Alpoim Guedes et al. 2013; Zhang and Hung 2010), one of the first regions to cultivate rice (e.g., Yan 1990; Zhang and Hung 2010). The connections with other regions remained strong during the Bronze Age,

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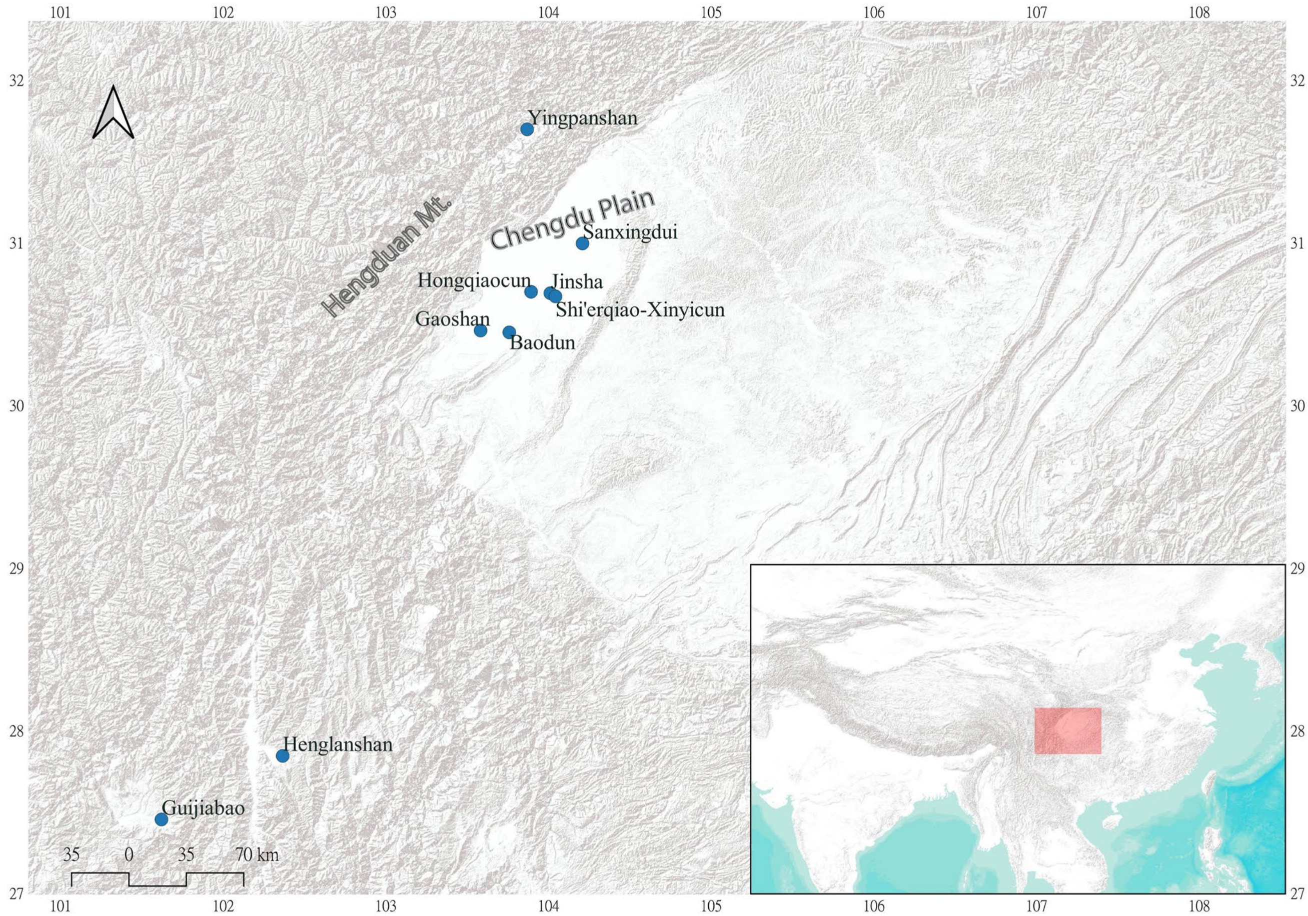

Fig. 1 Map showing the topography around the western Sichuan, including the Chengdu Plain and its western highlands (Hengduan Mt.)

suggested by the ritual paraphernalia found at the Sanxingdui (1700–1100 BC) and Jinsha (1000–800 BC) sites (e.g., Sichuan 1999; Falkenhausen 2003, 2011; Fald 2011; Flad and Chen 2013; Chengdu and Chengdu 2018; Lin 2019), the two largest settlement centers on the Chengdu Plain which flourished in succession after the decline of the Baodun Culture.

Under such intense interactions, the local communities might have been affected in many ways. For example, people might have changed their dietary patterns following migrations or from the introduction of new crops. They might also have moved to new places when they encountered environmental pressures. Direct chemical analyses on human remains, such as isotope analyses on human bone or tooth samples, may help us gain useful information on how the lives of these ancient people changed. However, related studies of the Chengdu Plain and the surrounding areas are still limited, mostly focusing on a single area of isotope studies, i.e., paleodiet (Lee et al. 2020a, b; Yi et al. 2020), and none or few of them have addressed human movements. To fill in this gap, in this study, tooth samples were collected from 39 human individuals excavated from the Jinsha, Hongqiaocun, and Shi'erqiao (Xinyicun) sites on the Chengdu Plain, the Yingpanshan site along the Upper Min River, and the Guijiabao site along the Yalong River drainage (Table 1 and Fig. 2). These samples were taken for strontium, oxygen, and carbon isotope analyses. In addition, for comparison, tooth samples from eight pigs (*Sus scrofa*) unearthed from the Jinsha and Shi'erqiao (Xinyicun) sites were also analyzed for supplemental data.

Our goal in this study was not only to investigate the effectiveness of isotopes in detecting dietary patterns, population movements, and climatic environments, but also to establish the local isotope baseline of the Chengdu Plain. This may also provide a comparison basis for future studies. In the following sections, the theories and applications of the several isotopic-analytical methods used in this project will be explained. The contexts where samples were drawn will then be introduced before the materials and methods used in laboratory analyses are described. The results will then be presented, followed by a discussion on paleodiets and ancient mobility. In the conclusion, the findings and their social implications will be presented. It is worth noting that while different isotopes may be informative in different

Table 1 Site names, periods, and information for the burials analyzed

Site (locus)	Period (BC)	Burial no	Sex[a]	Age (years)[b]
Guijiabao	3000–1700[1]	M1	I	5–6
		M2	I	I
		M11	I	I
		M12	I	I
Yingpanshan	1100–900[2]	M40	M	30–35
		M32	M	35–40
		T22-2	I	I
Hongqiaocun	ca. 2000–1700[4]	M52	M	30–40
		M53	M	35
		M54	I	6–7
Jinsha (Jinniu Chengxiangyitihua 5B)	ca. 1300–800[4]	M2152	I	8–10
		M2146	M	18–22
		M2151	I	10
		M1978	I	9
		M2156	I	I
		M1967	I	I
		M2053	M	25–30
		M1968	I	I
		M2013	I	I
		M2050	M	45–50
		M1980	I	I
		M2076	I	10
		M2037	I	I
		M2056	I	I
Jinsha (Zhixinjinshayuan I)	ca. 2000–1700[4]	M171	I	A
		M175	I	A
		M173	I	A
Jinsha (Yangguangdidai II)	1400–900[3]	M649	M	45
		M707	I	30–35
		M496	F	25
		M478	PM	30–35
		M756	PM	35–40
		M771	I	35–40
		M424*	F	30
		M425	M	40
		M386*	PF	30
		M387	PM	35–40
		M422	M	40
Shierqiao (XYC)	ca. 900–400[4,5]	NE12⑦:8	I	I

[a] *F* female, *PF* probable female, *I* indeterminate, *PM* probable male, *M* male

[b] *A* adult, *I* indeterminate

[c] *I* indeterminate

[1]Based on broomcorn grains and a human bone (Chengdu et al. 2017; Hao et al. 2022)

[2]The Yingpanshan site contains the Yingpanshan period: 3300–2600 cal. BC (based on five charcoal ^{14}C dating data, Chengdu et al. 2018) and the stone-coffin period: ca. 1100–900 cal. BC (based on unpublished ^{14}C dating data of two human bones)

[3]Based on four charcoal and two rice grains (Yan et al. 2017)

[4]Based on pottery types and strata (Chengdu 2004a, 2004b; Chengdu and Wenjiang 2009) and [5]also based on painted pottery (Yang et al. 2014)

[*] M386 included two individuals: one child lay with its head on the chest of one adult. M424 contained two layers of burials: a child on the top layer and an adult at the bottom

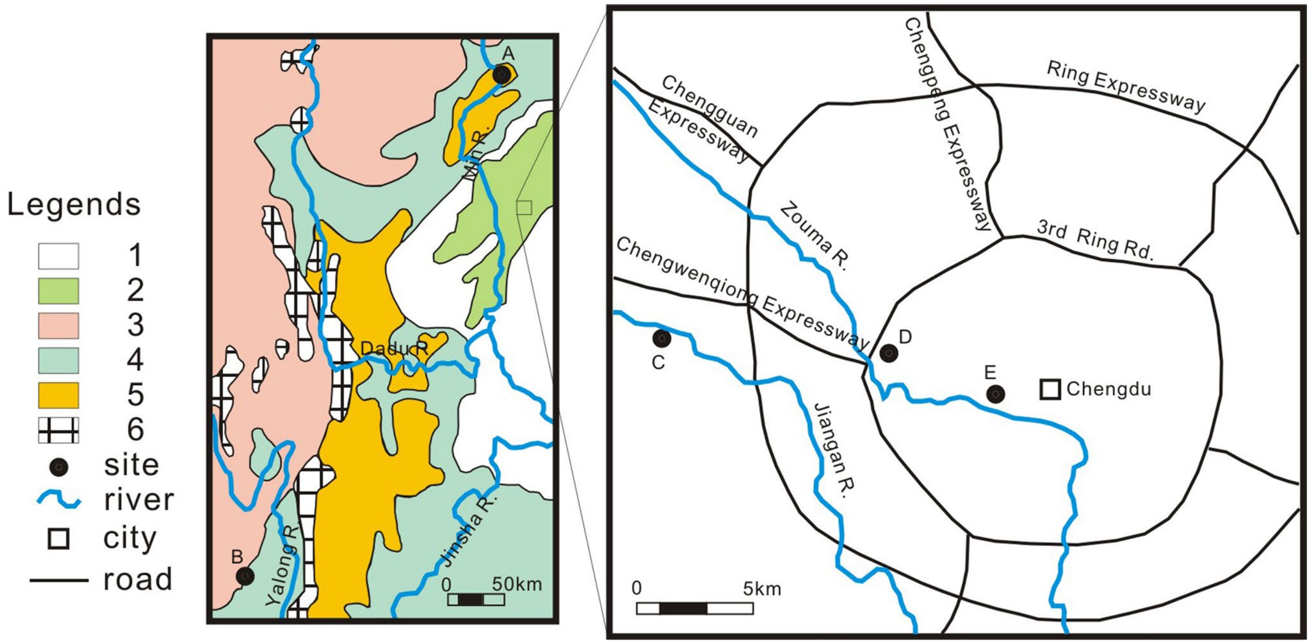

Fig. 2 Geological map of the study sites (redrawn from Chen et al. 2007). Left panel: simplified geological map of the area of study and the locations of the sites in the mountainous areas (Legend: (1) clastic rocks; (2) Quaternary fluvial deposits; (3) low-grade metamorphic rocks; (4) carbonate rocks; (5) high-grade metamorphic rocks; (6) granitoids; (A) Yingpanshan; (B) Guijiabao). Right panel: the sites on the Chengdu Plain mentioned in this study ((C) Hongqiaocun; (D) Jinsha; (E) Shi'erqiao and Xinyicun). The Yangguangdidai, Zhixinjinshayuan, and Jinniu Chengxiangyitihua 5B loci are located inside the Jinsha site

ways, they are not without limitations. It is the combination of multiple lines of evidence that gives us a better understanding of our research subjects.

Multi-isotopes: principles and reflections

Carbon isotopes

In this study, several isotopes are used to signify environments and identify human behaviors, including regional interactions in western Sichuan. Among them, carbon isotopes have been widely applied in recent decades to detect subsistence practices and dietary patterns (van Klinken et al. 2002; Richards et al. 2003; see also Katzenberg 2008). Specifically, carbon isotope composition ($\delta^{13}C$) is often used to differentiate C3 and C4 plants, which represent different pathways for the dark reaction of photosynthesis. However, the difference between C3 and C4 plants is not absolute or the same everywhere. Although plants, including the crops of concern in this study, can be categorized into these two groups, their carbon values may vary slightly area by area. We therefore need to test archaeobotanical remains more specifically to establish local baselines. In case local archaeobotanical data are not available, enough human or animal samples will be required to suggest a statistically meaningful range of ratios. For a region like the Chengdu Plain, in which the amount of rice remains is much larger than those of millet, the ratios of carbon isotopes are expected to reveal stronger C3 signals. This is especially true when contrasting regions that mainly grew millets, such as the Yellow River Valleys in northern China, where C4 signals dominated (Barton et al. 2009). Samples not yielding expected signals will therefore draw our attention. This gives carbon isotopes uses other than just identifying paleodiets and subsistence.

It should also be noted that dietary patterns often vary with social groups that are based on social status, gender, age, profession, or ethnic affiliation. Carbon isotopes therefore reflect combinational results of local environmental resources and social and cultural backgrounds. Certain people within a society who consume more meat or aquatic resources than others, for instance, might have easier access to these foods. This happened in our previous study, in which serial sampling was adopted to bisect individuals' first molars and second molars to investigate the dietary changes during their childhood and the weaning effect. By combining carbon and nitrogen isotopes extracted from their bone collagen, which reflect an average of the dietary patterns over many years before they died, the life history of the individuals under study can be reconstructed more comprehensively (see Lee et al. 2020b).

Strontium isotopes

Compared with carbon and nitrogen isotopes, strontium and oxygen isotopes are more commonly used to indicate mobility. Rations of $^{87}Sr/^{86}Sr$ have been successfully used to study paleomobility and to distinguish non-locals from locals (e.g., Knudson et al. 2017; Laffoon et al. 2018; Evans et al. 2019; Price et al. 2019, 2002). As ^{87}Rb decays to ^{87}Sr over time, older and Rb-richer bedrock tends to contain higher ^{87}Sr. Such an element existing in the soil is absorbed by plants and enters the food chain through herbivores. Therefore, the use of strontium isotopes to determine mobility requires knowledge of local geological conditions and strontium isotope ranges as revealed in plants or animals. However, while the strontium signature of one site is basically determined by the local geological context, recent studies have shown that this relationship may be more complicated than that (e.g., Laffoon et al., 2012). Bioavailable strontium is not just derived from bedrock but is affected by differential weathering, various surficial geological processes, atmospheric particles, sea spray, and cultural practices (Böhlke and Horan, 2000; Burton and Hahn 2016; Hedman et al. 2018). Further to this, it can be difficult to identify non-locals that come from areas with similar geological contexts (Bentley 2006). As a result, several approaches need to be used to complement each other to determine the bioavailable strontium range at any one site (Stantis et al. 2016).

As in the case of carbon isotopes, when local baselines are unavailable, statistical methods, along with basic geological information, are used to suggest a possible range of ratios (e.g., Bentley et al. 2007; Stantis et al. 2016). One commonly used approach is to use low-mobility animals as a proxy of the local baseline because these animals have limited feeding range (Bentley 2006; Price et al. 2019). Domestic pigs are usually thought to be suitable to establish the local strontium range because they are often raised near households and, in many cases, consumed human food refuse (Bentley 2006; Barton et al. 2009; Shaw et al. 2009; Chen et al. 2016). In particular, in previous studies on faunal remains on the Chengdu Plain as well as the Upper Min River, it was found that pigs were the most important meat source at related sites (He 2007; He et al. 2009, 2020; Lee et al. 2018:536–537). Studying the isotopic compositions of pigs not only helps us understand food webs, but also provides a way to assess environmental resources and animal husbandry (Frémondeau et al. 2012). Although in some cases, pigs might travel with humans for a long distance (e.g., Larson et al. 2010; Madgwick et al. 2019), "outliers" (nonlocals) are expected to be identified using statistical methods. Usually, tooth enamel is preferred for strontium sampling because it reflects the geological environment in which a child grows and therefore the growth of the teeth, without much modification thereafter (Bentley 2006). Tooth enamel is preferred also because it has been demonstrated to be more resistant to diagenetic alteration than bone and tooth dentine due largely to its higher crystallinity and stability (Koch et al. 1997; Kohn and Cerling 2002; Hoppe et al. 2003; Zazzo 2014). Consequently, in this study, the isotope compositions of tooth enamel are used to suggest both the diet and the mobility of prehistoric peoples.

Oxygen isotopes

In addition to strontium isotopes, the $\delta^{18}O$ values of tooth enamel may also be used to identify individuals' origins (e.g., Lamb et al. 2014), because the $\delta^{18}O$ value in the human body is determined by drinking water and thus reflects the $\delta^{18}O$ value of local precipitation (Sharp 2007; Zhang et al. 2015). The applicability of oxygen isotope ratio in migration studies has been discussed by many researchers (e.g., Britton et al. 2009; Henton 2010; Lightfoot and O'Connell 2016; Pollard et al. 2011; Madgwick et al. 2019; Pederzani and Britton 2019). However, it has been noted that, besides local precipitation, the oxygen isotope values are to some degree susceptible to other factors, including sources of moisture, atmospheric transport pathways, evaporation, altitude, amount of precipitation, and temperature. While how these factors affect $\delta^{18}O$ values has not been fully studied, some of them make it possible to use oxygen isotopes to track climate change. In the present study, δ18O values obtained from teeth were measured to complement the use of strontium isotopes to detect human migration from different river drainages or ecological systems.

These different isotopes reveal not only the characteristics of human beings themselves but also those of their foods and environments, reflecting the interaction between humans and their environment from different aspects. It is worth noting that while adapting to the environment, people also make choices from the available environmental resources according to some logic. In this study, samples were drawn from archaeological sites located in the lowland Chengdu Plain and from its highland neighbors. These settlements were located in different ecological systems and geological contexts but, nonetheless, maintained certain material-cultural exchanges. Such exchanges, together with the spread of subsistence practices, might also involve human mobility between the two regions. The isotopic studies in this paper are expected to advance our understanding of regional interactions. Nonetheless, as diets and mobility are often the results of the interaction between natural environments and social behavior, consideration of factors other than just ecofact remains and isotopic values are required.

Study sites

Yingpanshan site (31° 42′ 30.1″ N 103° 47′ 55.3″ E)

The Yingpanshan site (Fig. 1), at an elevation of 1500 m, is located on the largest basin of the Upper Min River, on which the largest known settlement of the northwestern Sichuan highlands was developed. This mountain range is also known as the Hengduan Mountain Range, or the eastern edge of the Qinghai-Tibetan Plateau. Based on the radiocarbon dating of charcoals recovered from the Neolithic layers, the site was occupied between 3300 and 2700 BC (Chengdu et al. 2018: pp. 515–516). Ecofact remains retrieved from these Neolithic layers revealed that millet agriculture and pig rearing were practiced during this time (He et al. 2009; Zhao and Chen 2011), adding more food sources to the already rich environmental resources that have been found from archaeological studies. The large number of millet further indicates that two kinds of millets, foxtail millet (*Setaria italica*) and broomcorn millet (*Panicum miliaceum*), were the most important crops.

Archaeological features and remains, including 11 residential foundations, 13 hearths, more than 120 ash pits, production areas for stone tools and pottery, and a possible public square, were also recorded (Chengdu et al. 2018). The possible public square was situated near the center of the settlement, surrounded by other house buildings and production spaces (Chengdu et al. 2018: pp. 18, 130). In addition, several sacrificial burials were uncovered, some of which were near the public square. However, their grave openings were often hard to detect, and thus their dates cannot be determined merely by archaeological stratigraphy. Among ten thousand artifacts found, painted pottery and stone tools, as well as subsistence strategies (i.e., millets and domestication of pigs), particularly reveal the close relationships between the region and its northern neighbors along the Upper Yellow River.

Above the Neolithic layers, approximately 190 stone-coffin burials and caches dating back to the Bronze Age were also found, although no habitation site has been discovered that was associated with them (Chengdu et al. 2013: p. 8). The human remains from the stone coffins were poorly preserved and after a major earthquake in 2008, during which the museum which was used to store the related archaeological remains collapsed, only one tooth was left that could be analyzed. The remaining burial goods suggest the different sources of influence. Not only were northern pottery styles present, but pottery types originating from the Chengdu Plain were also found. However, although the ecofact remains suggest that people in Yingpanshan consumed millets during the Neolithic Age, as mentioned above, the subsistence of the Bronze Age residents is not known to us without similar remains being found. It is only suspected that given the cooler and drier conditions, it may not have been easy for people to grow rice in these mountainous areas (d'Alpoim Guedes and Butler 2014; Gutaker et al. 2020).

In our previous study, we analyzed the carbon and nitrogen isotope compositions of the bone collagen of two sacrificial individuals (Fig. 3) that have previously been determined to be part of the Neolithic Period depositions and found that they mainly consumed C_3-based foods (Lee et al. 2020a, b). This finding aroused our attention regarding their origin, social status, and dates, because according to the archaeobotanical evidence, the subsistence at this site was dominated by millets. Recently, radiocarbon dating carried out by our team on the human bone samples confirmed that these burials actually belonged to a later period (1100–900 BC, Lin et al. under review) rather than to the Neolithic Period. That is, they were roughly contemporaneous with the stone-coffin burials but coincidentally intruded into the Neolithic layers. However, given the unusual burial custom, the possibility that these two individuals were non-locals still cannot be ruled out. Therefore, tooth samples from the two sacrificial burials and the one tooth from the stone-coffin burial were all collected in this study for examination (Table 1).

Guijiabao site (27° 26′ 26.2″ N 101° 37′ 03.0″ E)

The Guijiabao site (Fig. 1), at an elevation of 2400 m, was established in the Yanyuan Basin along a tributary of the Lower Yalong River in the mid-southern section of the Hengduan Mountains (Chengdu et al. 2017). Abundant remains, including at least 24 building foundations, 14 earthen-pit graves, two urn burials, and a considerable number of postholes, ash pits, stone knives and tools, and pottery have been unearthed (Zhou et al. 2019; Hao et al. 2022). Some graves contained an unknown number of individuals. They are difficult to identify due to poor preservation. The several piles of stone knives in gradient sizes (Fig. 4) are especially noticeable. Their style, however, is not unusual in the Hengduan Mountains, and similar stone tools were suggested to have been associated with agricultural harvesting (An 1955; Chen 2010; Chengdu et al. 2016c; Luo 2000; Luo and Li 2012). Whether the knives of various sizes were used to harvest different grains, used in different processing stages, or indicate the division of labor is unknown. Like the Yingpanshan site, the pottery remains at Guijiabao, some of which were found in the burials, reveal cultural exchanges with the northern settlements. In addition, subsistence strategies, burial customs, and pottery types at the Guijiabao site also suggest an affinity to those in northwestern Yunnan, or the southern section of the Hengduan Mountain (Hao et al. 2022).

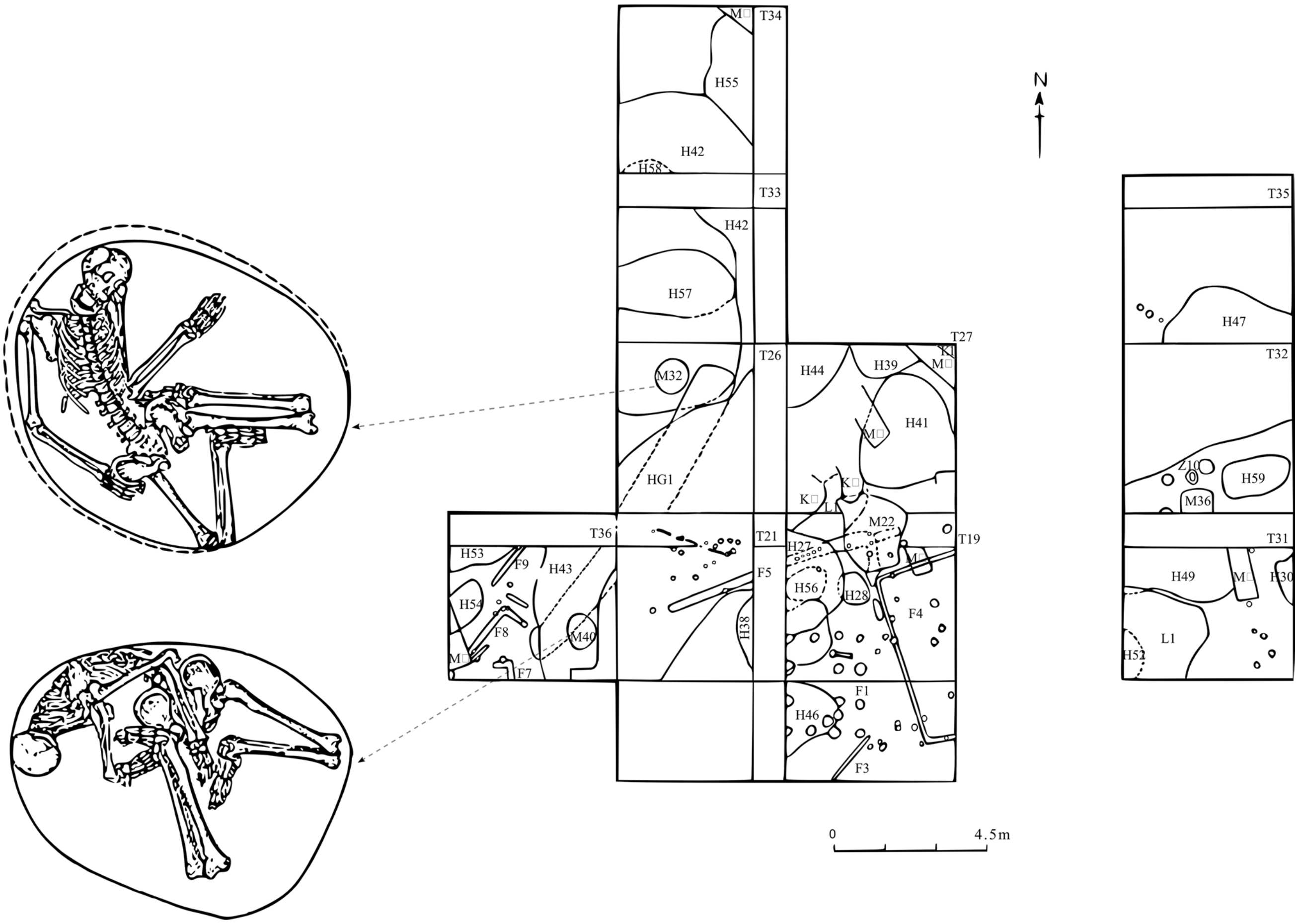

Fig. 3 Burials M32 and M40 from the Yingpanshan site (Redrawn from Chengdu et al. 2018: p. 238 Fig. 5–3, p. 249 Fig. 5–26, p. 5–28)

Fig. 4 One of the piles of stone knives found at the Guijiabao site (courtesy of Zhou Zhiqing)

Fig. 5 Burial M12 from the Guijiabao site. One tooth from this burial was used for isotope analysis (courtesy of Zhou Zhiqing)

Archaeobotanical study indicates that the crop grains unearthed from the site included foxtail millet, broomcorn millet, and a small amount of rice (Chengdu et al. 2016c). Radiocarbon dating on rice, broomcorn grains, and a human bone (M12) (Fig. 5) indicates that the site was mainly occupied between 3000 and 1700 BC (Chengdu et al. 2017; Hao et al. 2022), making the site one of the earliest in the Hengduan Mountains. The site was used until historic times.

In the Neolithic layers, in addition to crop remains, faunal remains of fish, horses, pigs, deer, and birds have been identified (Zhou et al. 2019). Tools for fishing and hunting were also discovered. Although only very few rice fragments were discovered in Guijiabao, giving no hints to rice domestication at the site, a nearby site, Henglanshan (2500–2000 cal. BC), clearly yielded amounts of rice along with two kinds of millets (Chengdu et al. 2016a, 2016b; Jiang et al. 2016), indicating that rice cultivation appeared in the region only at a slightly later time than on the Chengdu Plain. Given this early introduction of rice, its important role at these sites, and its coexistence with dry land crops (i.e., millets), it is possible that the middle-south Hengduan mountain area was another pivotal area, other than the Upper Min River and Chengdu Plain, where different species of animals and plants were introduced, coexisted, and also transmitted to neighboring regions. Such cultural exchanges connected regions around the Hengduan Mountain 5000 years ago, laying the foundation for the later Southwestern Silk Road.

The tooth samples analyzed in this study were collected from four human skulls (Table 1) unearthed in 2017 and 2018.

Hongqiaocun site (30° 41′ 31.0″ N 103° 53′ 24.0″ E)

The Hongqiaocun site (Fig. 1) is located on the bank of the Jiang'an River in the Wenjiang District of Chengdu City, which is close to and roughly contemporaneous with the Yufu walled enclosure (Chengdu et al. 1998; Chengdu 2001), one of the eight walled sites of the Baodun Period. The two sites also have comparable pottery types, representing the later phases of the Baodun Culture. In addition, the Hongqiaocun site is only 12 km away from the Jinsha site, the settlement center of the Bronze Age that will be introduced in the following section. After several years of systematic coring and excavations, pottery, ash pits, and stone tools belonging to the third phase of the Baodun Period (ca. 2000–1700 BC) were found (Chengdu and Wenjiang 2009; Yang 2015). About 400 graves, ten building foundations, ancient river courses, flooding deposition, and possible water management facilities, including water channels and banks for directing water flow, were also discovered (Chengdu 2016; Huang 2017; He et al. 2020; Jiang and He 2016). Among these facilities related to water management, a 147-m-long dike was built made of cobbles on the side of the water (Huang 2017), suggesting how the inhabitants might have struggled with, and to a certain degree, transformed the environment that would otherwise be easily flooded.

None of the burials contained any grave goods except one that was buried with an ivory staff, which has been speculated to be a scepter. Ivory ornaments were also found near the head and back of the deceased in this same burial, probably signifying the individual's social status. However, detailed information about the site and burials has not been published yet, and only very few human remains were available for analysis. In this study, tooth samples were collected from three human individuals with no grave goods (Table 1).

Jinsha site (late Baodun Period) (30° 40′ 45.1″ N 104° 00′ 29.7″ E)

The Jinsha site is a large site (ca. 500 ha) near the modern Chengdu city center (Figs. 1 and 2). So far, there are more than 70 excavated loci at this site (Chengdu and Chengdu 2017), but not all of the excavation reports on them have been published. The site developed into a settlement center during the early Bronze Age, or the Shi'erqiao Period (1200–500 BC). Before that time, the location was sparsely occupied by several small Neolithic settlements, one of which is the Zhixinjinshayuan locus, the first Baodun occupation locus discovered at the site. Based on the characteristics of the pottery, the locus is thought to have been occupied during the third phase of the Baodun Period (2000–1700 BC), roughly contemporaneous with the Hongqiaocun site.

During this time, people seemed to have migrated toward the modern Chengdu city center along several branches of the Lower Min River, especially the Modi River (Chengdu 2010a, 2010d:205; Jiang 2010; Zhou 2010). The Zhixinjinshayuan locus is situated in the southeastern sector of the Jinsha site which later developed along and spanned the Modi River. Although the excavation area is only 950 m^2, many Neolithic features, including three building bases, 21 ash pits, ten burials, one pottery kiln, and a large amount of pottery sherds, were found (Chengdu 2004a). Among the ten burials, eight individuals lay in an extended supine position, while the burial types of the other two are unknown. None of the burials had grave goods. Human remains were too poorly preserved such that only three-tooth samples were available for analysis (Table 1).

Jinsha site (Shi'erqiao Period) (30° 40′ 52.7″ N 104° 00′ 48.9″ E)

The Jinsha site became a settlement center, accompanying another center at the type site of the Shi'erqiao Culture, in the early Bronze Age in about 1000 BC (Chengdu and Chengdu 2017). At that time, the site included a sacrificial area, Meiyuan, situated nearly in the center (Chengdu 2004b; Chengdu and Chengdu, 2018; Zhu et al. 2004). There were also several large building foundations (Sanhehuayuan), residential areas, hundreds of simple pottery kilns, and cemeteries constituting the site, such as the Yangguangdidai II and the Jinniu Chengxiangyitihua 5B (Jinniu urban–rural integration no. 5B) loci included in this study. Beyond the northwestern end of Jinsha, there is a scattered number of small sites along the Modi and Jiang'an rivers, connecting the locations of Hongqiaocun and Jinsha (e.g., Chengdu 2005a, 2005b, 2005c, 2007a, 2007b, 2008a, 2008b, 2008c, 2010b, 2010c, 2010d; see also Jiang 2010, 2015; Lin 2019).

Although the Meiyuan sacrificial area that yielded a considerable amount of precious ritual items bearing special social meanings has attracted the most attention (Chengdu and Chengdu 2018), the several cemeteries included in the large compound associated with residential areas are important foci for investigating how multiple social groups might be incorporated into this urban center (Lin 2019). The Yangguangdidai II locus represents one such cemetery and is about 1 km from the sacrificial area. Based on the radiocarbon dating of charcoals and rice grains, this locus was used mainly between 1400 and 900 BC (Chengdu and Chengdu 2017:416). Archaeobotanical study suggests that both rice and foxtail millet prevailed at this locus (Yan et al. 2017). Faunal remains revealed that the inhabitants mainly consumed domesticated pigs and buffalo. Wild animals, such as deer, could also have been important supplementary meat in the inhabitants' diet (He 2017). During the 2003–2004 yearly excavation, 102 ash pits, 49 pottery kilns, 288 burials, and some small amounts of building remains were discovered (Chengdu and Chengdu 2017:13). This is where pottery kilns were most concentrated among all the loci in the Jinsha settlement (Yan et al. 2017).

All the burials found in this cemetery were in vertical earthen pits. Most of them were not furnished, while some had boat coffins with them (Chengdu and Chengdu 2017:411). They were primarily the first funerals with little or no burial goods. Although many human burials have been found at this cemetery, skeletons were generally not well preserved (Yuan and Zhou 2017:466), making it difficult to identify the age and gender of the individuals. Most of the skeletons were unable to be retrieved from excavation, leaving very limited samples. As a result, only eleven tooth samples from eleven individuals were available and collected (Table 1). Among the eleven individuals, eight lay in an extended supine position, a common position in the Chengdu Plain since the Neolithic, and two were in a sideway flexed position (M496 and M707). Such flexed position is rare in this cemetery and has raised the attention of the excavators (Chengdu and Chengdu 2017:411). The burial type of the last one is unknown. It is worth noting that while most burials contained a single individual, M386 contained two: a child was laid on the chest of an adult, possibly a female in her 30s (Yuan and Zhou 2017:467) (Fig. 6). In this burial, a tooth sample was collected from the adult individual. Another burial that seems abnormal is M387, which likely belongs to a male between 35 and 50 years old. The individual had a sign of porotic hyperostosis on the cranial vault (Yuan and Zhou 2017:468), possibly related to iron deficiency anemia or infectious diseases (see discussion of the disease in White and Folkens 2005:320; Walker et al. 2009). Besides human samples, one pig tooth from a burial (M423P), in which the human skeleton failed to be preserved, was also collected.

Tooth samples were also selected from 14 human individuals unearthed from the Jinniu Chengxiangyitihua 5B locus (Table 1), another cemetery inside the Jinsha site. The locus is near the remains of the large building compound, Sanhehuayuan, which is also close to but separated from Meiyuan by the Modi River. The large building is thought to be an important place for a public gathering where frequent communications and ideas were exchanged (Lin 2019). Jinniu Chengxiangyitihua 5B was excavated from 2006 to 2007 and turned out to be a part of a large cemetery, together with the Jinniu urban–rural integration no. 5A and 5C loci, the Gangzheng locus, and the Xiyan Yashe locus. The burial information has not been published yet, however. Based on the characteristics of the pottery, this locus was used between ca. 1300 and 700 BC, or the Shi'erqiao and the Xinyicun periods that will be discussed in the following section. Besides

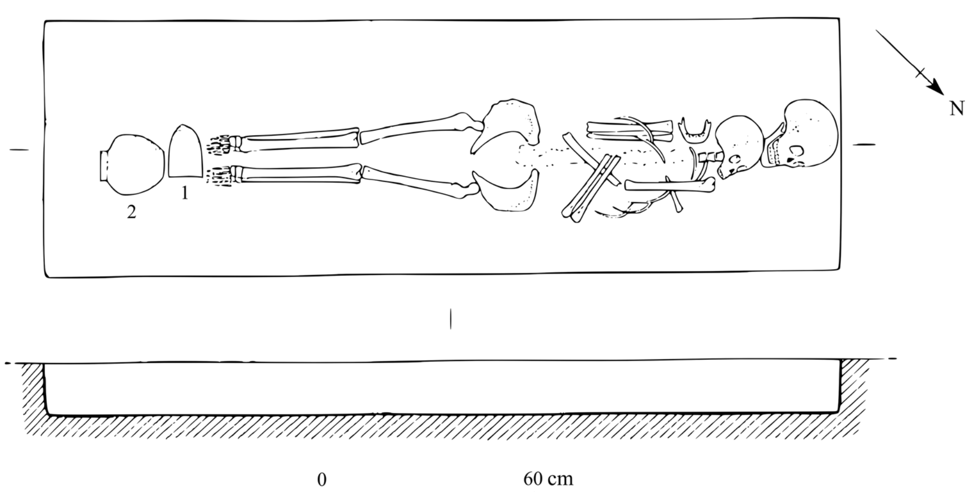

Fig. 6 M386 discovered from Yangguangdidai II locus (Redrawn from Chengdu and Chengdu 2017: p. 378, Fig. 453)

the cemetery, which contained 642 burials, the locus also consisted of 929 ash pits, 44 ditches, 41 pottery kilns, and two house foundations. Stone and jade tools, bronzes, and a large number of ceramics were found. Although no report regarding the ecofacts is available at this time, the flotation results from the no. 5C locus (Jiang et al. 2011), which once again suggests a rice-millet mixed subsistence with rice as the majority, may provide a clue. In addition, below the Bronze Age layers, Baodun remains, including 46 houses, 2 ash pits, and one burial, were discovered at this locus. It seems that the locus was once a densely populated area during the late Neolithic Age but later became a cemetery during the Bronze Age.

Shi'erqiao-Xinyicun site (Xinyicun Period) (30° 39′ 49.9″ N 104° 02′ 40.2″ E)

Another large settlement established on the Chengdu Plain during the Shi'erqiao Period is the type site, also called Shi'erqiao, which is only 5 km away from Jinsha (Fig. 1). The type site is characteristic of several big building structures that collapsed in situ (Sichuan and Chengdu 2009). These buildings suggest that the location was a special settlement. Though not containing a specific sacrificial zone as the one in the Jinsha settlement, it yielded ritual and valuable items. Throughout the Shi'erqiao Culture period, potters produced idiosyncratic pointed-bottomed vessels that were spread to regions beyond the Sichuan Basin, including the western highlands, both in burials and in cultural layers.

In 1995, excavation in the eastern section of this site yielded more discoveries, adding to those in the 1980s, including many pottery and stone artifacts, a small number of oracle bones and ritual items, and a human burial with bronze vessels, tools, and weapons (Chengdu 2004c). This location was named the Xinyicun locus, which mainly prevailed in the later period of Shi'erqiao (i.e., ca. 900–500 BC) and is also known as the Xinyicun Period (Chengdu 2004c). Pointed-bottomed vessels were still used in this period, with some of them having installed ring feet (Lin 2013:240). Similar ring-footed vessels were often used as grave goods in the western highlands, including the Yingpanshan stone-coffin cemetery mentioned above.

In the second excavation of Xinyicun in 2010, the locus further yielded more human burials and faunal bones. Large wooden structure remains, oracle bones, and other ritual items were also found (Chengdu 2014; Zhou et al. 2012). In addition, Baodun pottery was, for the first time, discovered in the domain of the Shi'erqiao type site (Zhou et al. 2012), suggesting that the locus had a long history of inhabitation. The wooden structure remains and ritual items, roughly contemporaneous with the Jinsha sacrificial zone, further indicate that the locus was a special part of the Shi'erqiao Culture, other than the Jinsha site.

Among the varieties of mammal bones found, those from pigs were the most common, followed by those from deer. This suggests that the animal protein in the Xinyicun diet came mainly from these two kinds of animals (Chengdu 2014). Although eight spatially unrelated skeletons were found in the deposits during the 2010 excavation (Yuan et al. 2021), only one human tooth was available for isotope analyses (Table 1). The tooth was found in the cultural layer, in which the burial had been completely destroyed in the taphonomy process. In addition, seven pig teeth were collected for analyses.

Overall, the three sites, Xinyicun, Hongqiaocun, and Jinsha site, which in turn contain Zhixinjinshayuan, Yangguangdidai II, and Jinniu Chengxiangyitihua 5B loci, are geographically close and together represent the isotopic values on the plain in contrast to the isotopic values of the sites in the western highlands from the late Neolithic Age to the Bronze Age. The sites in the mountainous areas, Yingpanshan and Guijiabao, form another contrast due to their different geographic locations, elevations, and geological and ecological environments. The materials used for analyses are described in the following section.

Materials and method

Materials

In this study, 47 tooth samples, including 39 from human individuals and eight from pigs, were collected from the aforementioned seven sites or loci. The first and second permanent molars were preferred whenever possible. All teeth were mechanically cleaned using aluminum oxide air abrasive to remove the surface dirt. Each surface-cleaned tooth was halved using a Buehler IsoMet with a diamond-tipped blade. The enamel sample was collected carefully from each tooth and any attached dentine was removed thoroughly by a clean diamond-studded drill bit. Following that, enamel samples were taken vertically, from the cusp to the cemento/enamel junction. Thus, each sample yielded an average value over the period of formation of the specific tooth. The samples were further crushed into powdered enamel and homogenized using an agate pestle and mortar.

Enamel oxygen and carbon isotope analysis

Approximately 9.0 mg of enamel powder was placed into a 2.0-ml micro-tube, to which 1.8 ml of laboratory-grade H_2O_2 solution (30% v/v) was added, and left for 48 h at room temperature in order to remove organic matter. During this interval, the samples were agitated several times by a Vortex device. The samples were then rinsed five times with 18-mΩ ultrapure water and centrifuged to ensure that the

H_2O_2 solution was removed completely. Afterward, 1.8 ml of 0.1 M of acetic acid (CH_3COOH) was added, and the samples were left for 4 h at room temperature for exogenous carbonate to be removed. The samples were rinsed again with 18-mΩ ultrapure water and then freeze-dried.

Enamel samples of approximately 3.0 mg were weighed into glass vials and analyzed for $\delta^{13}C_{VPDB}$ and $\delta^{18}O_{VPDB}$ on a Thermo Finnigan KIEL-IRMS at the Institute of Oceanography, National Taiwan University. Carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotope values were calibrated against in-house (marble) and international standards (NBS 19). Analytical precision based on repeated measurements of standards was ca. ± 0.1‰ for both isotopes (Supplementary Table 1). However, because the amounts of enamel are limited, these samples were not analyzed in duplicate to reproduce the same precision.

Strontium isotope and concentration analyses

Approximately 40 mg of enamel powder was collected for strontium isotope analysis. They were sent to the Department of Geological Sciences, University of Cape Town, where the following procedures for strontium isotope and concentration analyses were carried out.

After dissolution of enamel samples in a mixture of concentrated HNO_3, standard procedures for strontium separation were followed (Pin et al. 1994). The isotope ratio ($^{87}Sr/^{86}Sr$) of strontium was measured on a Nu Instruments NuPlasma HR MC-ICP-MS instrument, while strontium concentration was determined by using ICP-MS (Xseries2 Thermo Fisher). Analysis was referenced to an $^{87}Sr/^{86}Sr$ value of 0.710255 for the NIST 987. An in-house carbonate standard, NM95 (0.708915 ± 47, n = 125), measured alongside the samples, yielded a value of 0.708895 ± 21 (n = 10) (Supplementary Table 1).

Further to this, considering the above processes, without acid pretreatment, different results might be obtained; 15 out of 50 samples were randomly selected and sent to Isobar Science, where acid pretreatment was applied, for comparison. In this latter case, sample surface was cleaned by means of abrasion, and sub-samples were chosen from the most pristine part of the sample such that an average value during the tooth growth is obtained. Sub-samples were sonicated and rinsed with MilliQ water (18 mΩ) and dried at 40 °C. Sub-samples were then homogenized using the agate mortar and pestle. Sequential treatment with 0.1 N acetic acid using a ratio of 1.0 ml of acid for every ~20 mg of powder was applied to remove diagenetic contaminants (protocol number two by Hoppe et al., 2003). About 15 mg of homogenized sample was dissolved in 0.25 M HNO_3 to minimize leaching of strontium from detrital/clay residues.

Low-blank separation of strontium from each sample was accomplished by extraction chromatography using *Eichrom* Sr resin. This procedure follows the methods proposed in Pourmand et al. (2014) and Pourmand and Dauphas (2010). High-precision strontium isotope analysis was performed on a Thermo Fisher Neptune PlusTM MC-ICP-MS and a quartz stable sample introduction (SSI) system.

The measured 87Sr/86Sr ratios were corrected for mass bias and isobaric interferences and the final ratio was adjusted relative to the accepted value of 0.710248 ± 0.000003 (McArthur et al. 2001) for SRM 987, enabling comparison with literature measurements of radiogenic strontium isotopes. Every 1–5 sample measurements were bracketed with measurements of two SRM 987 standard solutions at 100 ng g^{-1}. For the current measurement, the strontium isotope method uncertainty of the NIST SRM 987 standard solution is ± 0.000005 (%95 CI) for 87Sr/86Sr.

The results are presented in Table 2. It turns out that there is no significant difference between the results of the two laboratories (Mann–Whitney test, $W = 347$, p-value = 0.2246 > 0.05). We use the results of the Department of Geological Sciences, University of Cape Town, for consistency for the following discussion.

Results

Because of the proximity of Hongqiaocun, Jinsha (including Zhixinjinshayuan, Yangguangdidai II, and Jinniu Chengxiangyitihua 5B), and Xinyicun to each other, and also because of the variances between each pair of these sites/loci are no more obvious than the variances within individual sites/loci, these sites and loci are treated as a whole. They together represent the isotopic measurements of the Chengdu Plain.

All isotope analytical results are listed in Tables 2 and 3 and presented in Figs. 7 and 8. The results are also described below.

Carbon isotope values

Human samples collected from the Chengdu Plain, including sites at Hongqiaocun, Jinsha, and Xinyicun, exhibited a large $\delta^{13}C$ range between − 13.8 and − 1.5‰ (median = − 12.3‰, IQR = 1.9‰; mean = − 10.9 ± 3.1‰, 1σ, n = 32). This wide range was caused by several extremely high values (e.g., M386 and M387 from the Yangguangdidai II locus, and M2151 and M2076 from the Jinniu Chengxiangyitihua 5B locus). They cause the data to skew to the right and were suspected to be outliers. After calculating the interquartile range and its outlier fences, these high values were excluded as outliers. The remaining samples revealed a smaller range between − 13.8 and − 8.1‰ (median = − 12.5‰, IQR = 1.6‰; mean = − 12.0 ± 1.3‰, n = 28). The values of pig samples were not significantly different from those of the human samples (Mann–Whitney test, $W = 161$, p-value = 0.0645 > 0.05) with a range between − 14.3 and − 9.3‰ (median = − 13.6‰, IQR = 1.8‰; mean = − 12.9 ± 1.7‰, 1σ, n = 8).

Table 2 The strontium, carbon, and oxygen compositions of human tooth enamel from prehistoric sites of Sichuan

Site (locus) [a]	Burial no	Tooth sampled [b]	Estimated age (years) of enamel formation [c]	$\delta^{13}C_{VPDB}$ (‰)	enamel $\delta^{18}O_{VPDB}$ (‰)	$^{87}Sr/^{86}Sr \pm 2std$ [d]	Sr (ppm) ± %RSD	$^{87}Sr/^{86}Sr$ Adjusted [e]	± 95% CI
GJB	M1	LM_1	Birth–3	− 5.6	− 13.3	0.708743 ± 0.000010	158 ± 0.295	0.708695	0.000024
	M2	LM_1	Birth–3	− 7.2	− 11.8	0.708987 ± 0.000014	110 ± 0.375		
	M11	Tooth fragment	-	− 3.4	− 12.3	0.708550 ± 0.000012	129 ± 0.419	0.708526	0.000017
	M12	Tooth fragment	-	− 5.6	− 9.3	0.709128 ± 0.000011	145 ± 0.218		
YPS	M40	RM_2	3–8	− 10.6	− 8	0.711923 ± 0.000012	n.a		
	M32	RM_1	Birth–3	− 9.9	− 8.6	0.711858 ± 0.000010	n.a		
	T22②	RM_2	3–8	− 6.4	− 8.8	0.715564 ± 0.000016	206 ± 0.281	0.716343	0.000018
HQC	M52	LM_2	3–8	− 12.6	− 10.5	0.713143 ± 0.000012	177 ± 0.300	0.71315	0.00002
	M53	RM_2	3–8	− 11.2	− 10.1	0.713012 ± 0.000008	145 ± 0.337	0.713014	0.000034
	M54	LM^1	Birth–3	− 12.6	− 10.4	0.713056 ± 0.000009	159 ± 0.518		
Jinsha (JN5B)	M2152	LM^1	Birth–3	− 12.8	− 8.5	0.713357 ± 0.000013	301 ± 0.919		
	M2146	LM^1	Birth–3	− 10.9	− 7.8	0.713284 ± 0.000014	449 ± 1.226		
	M2151	RM_2	3–8	− 3.8	− 7.2	0.712265 ± 0.000012	161 ± 0.243	0.712295	0.000013
	M1978	RM^1	Birth–3	− 13.8	− 8.3	0.713301 ± 0.000010	235 ± 0.219		
	M2156	LM^1	Birth–3	− 10.9	− 8.0	0.713203 ± 0.000010	455 ± 0.386		
	M1967	RM^2	3–8	− 9.8	− 8.6	0.713180 ± 0.000010	273 ± 0.494	0.713208	0.000011
	M2053	LM^2	3–8	− 11.6	− 7.5	0.713018 ± 0.000011	260 ± 0.360		
	M1968	RM^2	3–8	− 12.1	− 7.7	0.712964 ± 0.000011	248 ± 0.325	0.710679	0.00002
	M2013	RM^2	3–8	− 12.7	− 9.4	0.712721 ± 0.000012	165 ± 0.256		
	M2050	LP^1	3–7	− 12.6	− 9.0	0.713215 ± 0.000011	250 ± 0.561		
	M1980	RM_2	3–8	− 13.5	− 7.6	0.713311 ± 0.000011	523 ± 0.453		
	M2076	Lm_2	In utero–1	− 4.6	− 7.5	0.712270 ± 0.000011	167 ± 0.230	0.712288	0.000021
	M2037	RM^1	Birth–3	− 13.2	− 7.4	0.713259 ± 0.000013	229 ± 0.133		
	M2056	LM^1	Birth–3	− 12.8	− 7.6	0.712102 ± 0.000012	139 ± 0.497	0.712141	0.000008
Jinsha (ZX)	M171	Molar	-	− 10.5	− 10.0	0.713992 ± 0.000009	233 ± 0.352	0.713964	0.000013
	M175	RM^3	8–14	− 11.9	− 10.1	0.713263 ± 0.000013	227 ± 0.136		
	M173	LM^3	8–14	− 12.4	− 10.0	0.713366 ± 0.000013	236 ± 0.225	0.713242	0.000027
Jinsha (YG)	M649	LM^2	3–8	− 12.4	− 7.8	0.713207 ± 0.000009	429 ± 0.410		
	M707	LM_2	3–8	− 12.8	− 8.4	0.712598 ± 0.000011	249 ± 0.142		
	M496	RM^2	3–8	− 12.6	− 7.5	0.712851 ± 0.000013	207 ± 0.161		
	M478	RM_1	Birth–3	− 12.7	− 8.2	0.713346 ± 0.000009	341 ± 0.261		
	M756	RM_2	3–8	− 12.2	− 7.4	0.713025 ± 0.000011	235 ± 0.173		
	M771	LM_2	3–8	− 11.1	− 8.3	0.713215 ± 0.000013	382 ± 0.639		
	M424	RM_2	3–8	− 12.7	− 8.8	0.713235 ± 0.000009	453 ± 0.276		
	M425	LM^1	Birth–3	− 13.0	− 7.7	0.713524 ± 0.000012	906 ± 0.771		
	M386	RM^1	Birth–3	− 1.5	− 6.6	0.712268 ± 0.000010	232 ± 0.465	0.712045	0.000026
	M387	RM_1	Birth–3	− 4.8	− 7.4	0.712791 ± 0.000012	227 ± 0.452		
	M422	RM_2	3–8	− 9.8	− 8.5	0.712186 ± 0.000009	251 ± 0.350	0.712198	0.000011
Shierqiao (XYC)	NE12⑦:8	LM_2	3–8	− 8.1	− 7.9	0.711835 ± 0.000009	177 ± 0.631	0.711712	0.000016

[a] *GJB*, Guijiabao site; *HQC*, Hongqiaocun site; *JN5B*, Jinniu Chengxiangyitihua 5B locus; *ZX*, Zhixinjinshayuan I locus; *YPS*, Yingpanshan site; *YG*, Yangguangdidai II locus; *XYC*, Xinyicun locus

[b] *R*, right; *L*, left; *M*, permanent molar; *m*, deciduous molar; *P*, permanent premolar

[c] Based on AlQahtani et al., (2010)

[d] Results generated by the Department of Geological Sciences, University of Cape Town

[e] Results generated by Isobar Science

[*] When the strontium concentration > 500 ppm, the strontium isotope value is excluded

n.a., non-analyzed

Table 3 Results of strontium, carbon, and oxygen isotope analyses of pig tooth enamel

Site (locus)	Sample no	Tooth sampled [a]	$\delta^{13}C_{VPDB}$ (‰)	$\delta^{18}O_{VPDB}$ (‰)	$^{87}Sr/^{86}Sr \pm 2std$	Sr (ppm) ± %RSD
Jinsha (Yangguangdidai II)	M423P	Molar	− 12.5	− 9.1	0.712784 ± 0.000013	215 ± 115
Shierqiao (Xinyicun)	TN05W09⑨	LM_2	− 14.3	− 8.3	0.713207 ± 0.000014	289 ± 0.384
	TN08W06⑨:68	RM_1	− 13.4	− 9.0	0.713207 ± 0.000015	319 ± 0.392
	TN07W07⑨:1	RM_1	− 14.1	− 6.6	0.713043 ± 0.000021	250 ± 0.404
	TN05E01⑨:41	LM_1	− 11.8	− 6.2	0.711700 ± 0.000016	176 ± 0.141
	TN01W03⑩:14	RM_1	− 14.1	− 8.4	0.713074 ± 0.000009	282 ± 0.621
	TN03W06⑨	RM_3	− 9.3	− 7.2	0.712100 ± 0.000013	294 ± 0.350
	TN08W07⑨	Molar	− 13.7	− 11.9	0.712736 ± 0.000014	226 ± 0.245

[a] *R*, right; *L*, left; *M*, permanent molar

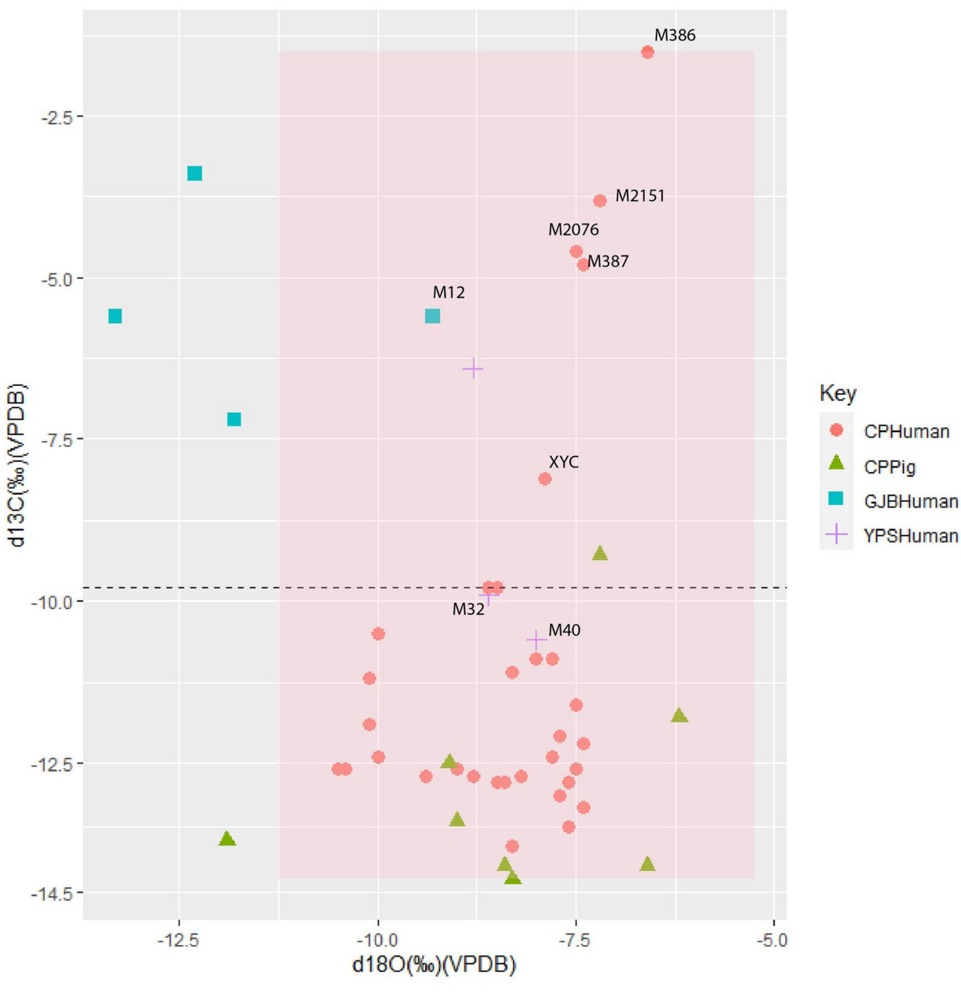

Fig. 7 Scatter plot of $\delta^{13}C$ versus $\delta^{18}O$ values of humans and pigs. CPHuman, Chengdu Plain humans; CPPig, Chengdu Plain pigs; GJBHuman, Guijiabao humans; YPSHuman, Yingpanshan humans. The horizontal dashed line shows the rough boundary between C_3- and C_4-based diets. The shadow area indicates the potential local $\delta^{18}O$ range (− 11.25– − 5.25‰) of the Chengdu Plain. Some interesting cases are labeled (XYC, Xinyicun human remains; M386 and M387 are from Yangguandidai II locus; M2076 and M2151 from Jinniu Chengxiangyitihua 5B; M32 and M40 from Yingpanshan; M12 from Guijiabao)

By comparison, the three Yingpanshan samples from the mountain areas can be divided into two groups based on the $\delta^{13}C$ values and on the burial customs. The first group contained one sample (T22②) taken from the individual buried in the stone coffin. This sample showed a high value (− 6.4‰). Another two samples, M32 and M40, coming from the sacrificial burials, had lower values (− 9.9‰ and − 10.6‰, respectively). It is worth noting that this second group fell within the range of the 28 Chengdu samples.

The $\delta^{13}C$ values of the four Guijiabao samples, on the other hand, varied between − 7.2 and − 3.4‰, which were very different from those of the samples from the Chengdu Plain and closer to the value of the Yingpanshan stone-coffin burial. The drastic difference in the $\delta^{13}C$ values between those from the Chengdu Plain and those from the other two

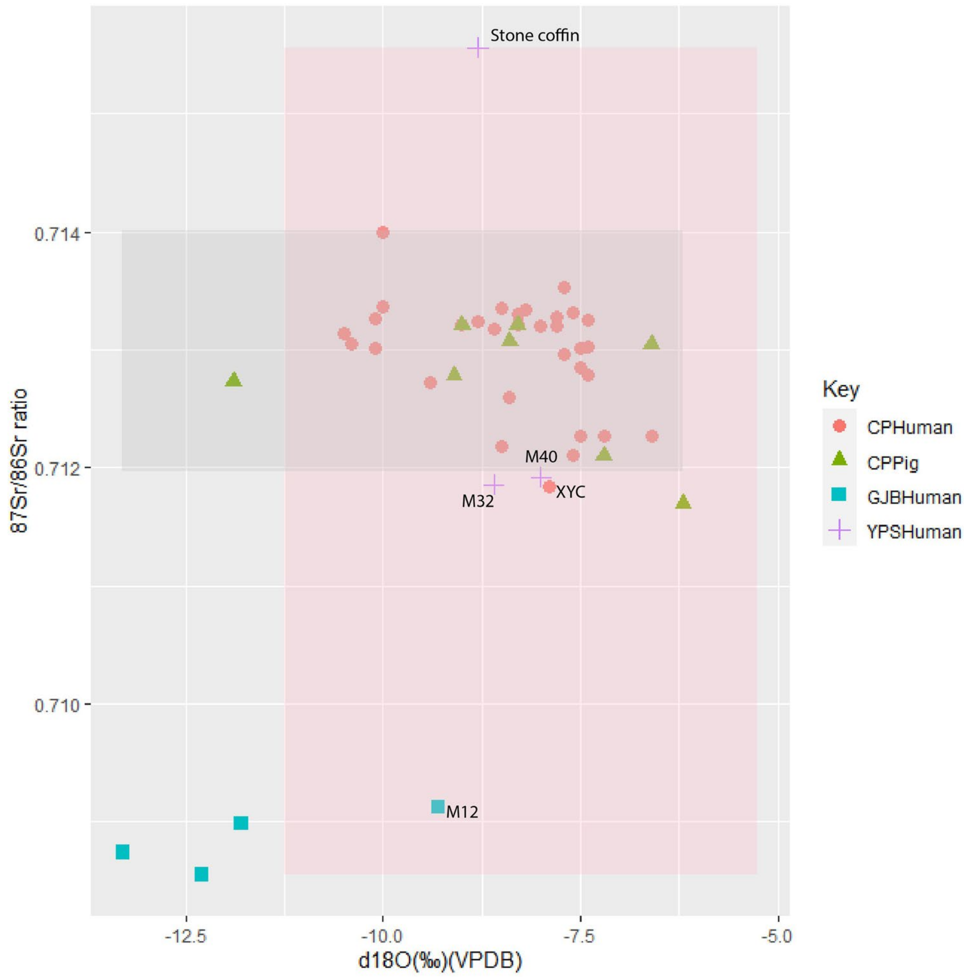

Fig. 8 Scatter plot of the $^{87}Sr/^{86}Sr$ ratios versus $\delta^{18}O$ values of humans and pigs. CPHuman, Chengdu Plain humans; CPPig, Chengdu Plain pigs; GJBHuman, Guijiabao humans; YPSHuman, Yingpanshan humans. The potential $^{87}Sr/^{86}Sr$ local range of the Chengdu Plain (in gray shadow) (0.71197–0.71400) is defined by pigs and humans together. The pink band indicates the potential local $\delta^{18}O$ range (−11.25–−5.25‰) of the Chengdu Plain. Some interesting cases are labeled (XYC, Xinyicun human remain; M32, M40, and stone coffin are from Yingpanshan; M12 from Guijiabao)

sites coincides with the invisible boundary between the lowland plain and the highlands, reflecting their landforms and ecosystems.

Oxygen isotope values

Breastfeeding may enrich ^{18}O in developing tissues, such as those in the permanent first molar and deciduous teeth (Britton et al. 2015; Wright and Schwarcz 1998). That is, ^{18}O contained in these two tooth types is normally slightly higher than other teeth. However, the difference (−0.7‰) is very small and does not cause difference in identifying non-locals in this study. This nursing effect is therefore not taken into account here.

As a result, the $\delta^{18}O$ values for the human samples from the Chengdu Plain ranged between −10.5 and −6.6‰ (median = −8.1‰, IQR = 1.3‰; mean = −8.4 ± 1.1‰, $n = 32$). For the eight pig samples, their $\delta^{18}O$ values were not significantly different from those of the human samples (Mann–Whitney test, $W = 121$, p-value = 0.8259 > 0.05), suggesting that pigs and humans might have shared similar water sources. After one pig sample falling outside the lower outlier fence (< −11.3‰) is excluded, the other samples together produced values ranging from −10.5 to −6.2‰, with a median of −8.2‰ and an IQR of 1.4‰ ($n = 39$). These values could describe the potential local $\delta^{18}O$ range of the Chengdu Plain. This range is in line with the weighted $\delta^{18}O$ values (−10.5–−4‰, mean = −7‰) of the precipitation on the Chengdu Plain, based on the measurements of the Global Network Isotopes in Precipitation (GNIP) project (see Yu et al. 2014) and is also consistent with the precipitation $\delta^{18}O$ values measured in Mao Xian (−11.98–0.31‰, mean = −7.77‰), where the Yingpanshan site is located (Liu et al. 2014).

All the $\delta^{18}O$ values of the three Yingpanshan samples from the mountain areas ranged from −9.3 to −8.0‰, falling within the $\delta^{18}O$ range of the samples from the Chengdu Plain. The value (−9.3‰) of one of the Guijiabao samples (M12) also fell within the range, while the other three samples had lower values, from −14.0 to −12.3‰. These latter three data distinguish the $\delta^{18}O$ range of the Yalong River drainage from that of the Min River.

Strontium isotope ratios

The $^{87}Sr/^{86}Sr$ range of the 32 human samples from the Chengdu Plain fell between 0.71184 and 0.71399 (median = 0.71316, IQR = 0.00049; mean = 0.71298 ± 0.00048). The eight pig samples had ratios ranging between 0.71170 and 0.71321(median = 0.71291, IQR = 0.00053; mean = 0.71273 ± 0.00055). There was no significant difference observed between the two datasets (Mann–Whitney test, $W = 173$, p-value = 0.1323). We chose to adopt a broader range by combining the two ranges together to suggest the bioavailable strontium baseline of the Chengdu Plain, which is 0.71170–0.71399. When the interquartile range and its outlier fences (0.71197–0.71400) based on these human and pig samples are calculated, one human and one pig samples, both from the Xinyicun locus, fell outside the range values. However, it should be noted that this range is based on our currently available samples and are not definite.

In the mountainous areas, once again, the $^{87}Sr/^{86}Sr$ ratios of the three Yingpanshan samples can be divided into two groups. The sample derived from the stone-coffin burial displayed an extremely high ratio (0.715564). On the other hand, the other two samples collected from the sacrificial burials revealed lower ratios (0.711858 and 0.711923), close to the value range of the samples taken from the Chengdu Plain.

By comparison, the ratios of the four Guijiabao samples were even lower, ranging from 0.708550 to 0.709128. Again, this signifies the difference between the value range of the Min River drainages and that of the Yalong River watershed.

Discussion

Paleodiets

From the above results, it is found that the Guijiabao individuals had higher $\delta^{13}C$ values (− 7.2– − 3.4‰), indicating a considerable contribution of C_4-based foods to their diet. Based on the archaeobotanical study, the most likely source was the two kinds of millets, particularly foxtail millet (Chengdu et al. 2016c). When the $\delta^{13}C$ values of − 24.9‰ and − 10.2‰ for Sichuan archaeological rice and millet grains, respectively (Lee et al. 2020a), and a trophic shift of 11.5‰ between the diet and tooth enamel (i.e., $\delta^{13}C_{enamel} - \delta^{13}C_{diet} = 11–12‰$, Fernandes et al. 2012; Gregoricka et al. 2017; Harrison and Katzenberg 2003) are taken into account, the contribution of millets to the diet of the Guijiabao people is higher than that of rice (supplementary table 2). This result, combined with the archaeobotanical evidence, suggests that foxtail millet was a main food resource at the Guijiabao site. Situated in the location where the northern and southern sections of the Hengduan Mt. Range meet, the subsistence of the Guijiabao site shows affinity to its northern counterpart while the pottery reveals more similarities to the southern part of the Hengduan Mt., where rice dominated. The transitional characteristics of Guijiabao deserve further studies to acquire details.

The situation at the Yingpanshan site seems even more complicated. The sample taken from the stone-coffin burial showed a strong C_4 signature. This result suggests that millet might have been an important food source during the Bronze Age. Flotation of soil samples from the Neolithic layers at this site has revealed that plant assemblages were dominated by broomcorn millet and foxtail millet (Zhao and Chen 2011). In addition, the $\delta^{13}C$ values of the Neolithic pig bones showed that pigs were raised mainly by feeding with millet (Lee et al. 2020a). Combining all the lines of evidence, one might expect that dry farming of millet was practiced in the Upper Min River throughout the Neolithic Period and Bronze Age.

However, the $\delta^{13}C$ values of the two sacrificed individuals at the Yingpanshan site had values contrary to this expectation. The lower $\delta^{13}C$ values of their teeth indicate that they consumed large amounts of C_3-based foods. The $\delta^{13}C$ values of their bone collagen also led to the same indication (Lee et al. 2020a). These findings are inconsistent with the archaeobotanical and isotopic evidence mentioned above. In our previous study, we proposed several possibilities for such an inconsistency, one of which was that the two sacrificial individuals were non-locals (Lee et al. 2020a). In this study, the strontium isotope analysis adds further evidence for this assumption (see discussion below).

Unlike the C_4-based diet of the people at the mountain sites, the diets of human individuals and pigs on the Chengdu Plain were mainly composed of C_3-based foods. Paleoethnobotanical study suggests that rice was the most likely C_3 food since the first phase of the Baodun Culture (e.g., d'Alpoim Guedes et al. 2013), though there might be a minor contribution from wild C_3 plants in the food chain, especially because some wild animals, such as deer, were very likely a supplementary source to the people's diet (e.g., He 2017). In addition, the $\delta^{13}C$ values of the human bone collagen and rice grain at the Gaoshan site (2500–2000 BC) (Jiang and Yan 2017; Lee et al. 2020a), a Baodun Culture walled site about 14 km from the Baodun type site and 50 km from the Chengdu City, also supports the argument that rice was the major food source for people of the Baodun Culture. As a result, such consistent C_3 signatures in the tooth enamel of most human individuals and pigs lead to the conclusion that rice agriculture played an important role in the subsistence system of the people on the Chengdu Plain, at least from the early Baodun Period on. In such circumstances, we should expect a general C_3-based diet pattern, or lower $\delta^{13}C$ values, for the people and pigs on the Chengdu Plain, compared with that those in the mountainous areas.

However, although rice became a crucial food source, millet did not completely disappear, because it might have increased the diversity of subsistence and reduced the risk of famine from crop failure (d'Alpoim Guedes 2011; Huo 2009). The proportion of foxtail millet seems to have varied by location during the Shi'erqiao Period and may be even slightly higher than rice in the Yangguangdidai II locus. One possible reason is that the sampling location might be a place where millets were processed after being harvested (Yan et al. 2017). Given the sometimes high proportions of millet as supplementary crops, it should not be surprising to find some C_4 signal in human or animal remains. In fact, in our study, one Xinyicun pig remain had a higher $\delta^{13}C$ value than the others, suggesting that millet was occasionally used as fodder as well. In addition, several human remains with high values of $\delta^{13}C$ were also observed—M386 and M387 at the Yangguangdidai II locus, and M2151 and M2076 at the Jinniu Chengxiangyitihua 5B locus—indicating that these individuals consumed more millet than others. Possible explanations for the heavy reliance on millet by the four individuals are that they were non-locals or were treated differently according to gender or social status. However, based on their $^{87}Sr/^{86}Sr$ ratios, these individuals had similar ratios as others. The assumption that they were non-locals can be ruled out unless they were from regions with the same strontium signature (see discussion below).

So far, we have very little evidence to confirm the other possibilities because the preservation conditions of the burials were not good, leaving details unknown. The only thing we know is that the two cases consumed more millet at Jinniu Chengxiangyitihua 5B both died very young (at about 10 years old). As for the cases in the Yangguangdidai II locus, M387 was interred in an extended supine position, with few ceramics (Chengdu and Chegndu 2017). He was also found to have a sign of porotic hyperostosis on his cranial vault, as mentioned above (Yuan and Zhou 2017:468). On the other hand, although M386 seems unique in that it contained one child and one adult in the same grave pit (Fig. 6), both individuals lay in the extended supine position. This burial included only one pointed-bottom vessel (*jiandiqi*) and one jar with a high collar (*gaolingguan*) as grave goods (Chengdu and Chengdu 2017:378), both of which are not unusual at the Jinsha site. Consequently, according to their burial orientations (NW–SE), positions, and goods, the individuals who consumed more millet than others did not seem to have a different social status from the others. It has also become clearer that the dietary pattern was not associated with burial positions, regardless of whether the skeletons were extended or flexed. Although such a dietary pattern with a tendency to millet seemingly has implications for the nutritional condition of the individuals, it is, however, difficult to explain their unique diet simply from this archaeological information. More archaeological backgrounds or samples are needed to understand the reasons for the unusual diet.

Locals and non-locals

The wide range of $^{87}Sr/^{86}Sr$ values in these Chengdu Plain sites may reflect the formation of the Quaternary fluvial deposition in this region, which contains mainly terrigenous clast accumulation and consists of sediments in the alluvial fans and frontal alluvial plain that are shaped by the rivers traversing Longmen Mountain (i.e., Min River and Tuo River) (Zhao et al., 2015). As the strontium isoscape of the Plain is not available, our data provide a statistic model to assess the bioavailable range. Judging from the results of the above strontium analysis, one human remain and one pig remain from the Xinyicun locus fell outside the local range and can be tentatively considered to be non-locals according to the current data. The $^{87}Sr/^{86}Sr$ measurements of these two outliers are rather close to those of the pig remains we obtained at the Neolithic Baodun and Gaoshan sites (median = 0.71193, IQR = 0.00119, unpublished data) in the Xiejiang River, a tributary of the Lower Min River. However, given that the Xinyicun individual consumed more millet than other Chengdu Plain peoples, the origin of the Xinyicun individual remains uncertain. On the other hand, it has long been proposed that immigrants from the east once affected the societies of the Bronze Age Chengdu Plain. It is not uncommon for pottery types of eastern Sichuan to appear in the Chengdu Plain (e.g., Jiang 2007) and this is also true in Xinyicun (Zhou et al. 2012). Eastern Sichuan, where millet crops dominated and are geologically composed of Yangtze Carbonate Platform with massive dolomite (avg. $^{87}Sr/^{86}Sr = 0.71052$) (Jiang et al. 2019), becomes a possible origin for the non-local individual in Xinyicun. There is, however, no further evidence to suggest the individual's identity.

As one Xinyicun pig remain was identified as an outlier and the IQR of all pig remains we examined in this study is slightly larger than that of humans, the origin of the pigs does not seem to be concentrated. Examples elsewhere (Madgwick et al. 2019) draw our attention to the presence of exotic pigs that would not have easily traveled long distances in prehistoric times. This also highlights the particularity of the place and the special role of pigs in social events (Luo, 2012; Lander et al. 2020). The presence of ritual items, outsider, objects of foreign styles, and exotic pig furthers the possibility that Xinyicun may have been a place of special meaning.

In the mountainous areas, the Yingpanshan individual excavated from the stone-coffin burial showed a very high $^{87}Sr/^{86}Sr$ ratio (0.71556), probably reflecting the more radiogenic terrain of the site, which is composed of Sinian high-grade metamorphic rocks (Fig. 2), as observed by Zhao et al. (2015). As plant samples collected at sites have been shown to be highly correlated with the strontium isotope ratios of soil and are useful in reconstructing the bioavailable baselines (Britton et al. 2020), we have adopted this method to collect plants at Yingpanshan and obtained measurements ($^{87}Sr/^{86}Sr = 0.71444$ and 0.71424, unpublished data) close to that of the stone-coffin burial. They are clearly distinguishable from the samples of the Chengdu Plain. On the other hand, the other two individuals excavated from the sacrificial burials had lower ratios (0.71186 and 0.71192), which are close to the strontium range of the Chengdu Plain, especially the Xiejiang River basin. It seems very likely that the two sacrificed individuals came from the Chengdu Plain, if the presence of Chengdu Plain materials at Yingpanshan is also taken into account. This result helps explain our previous finding that they ate more C_3-based foods, similar to what most individuals who lived on the Chengdu Plain ate.

As for the Yalong River drainage, the four Guijiabao individuals displayed lower $^{87}Sr/^{86}Sr$ ratios (0.708550–0.709128) than those of the individuals at the other two places, probably reflecting the bedrock formations along the Lower Yalong River, which are composed of Paleozoic carbonates and low-grade metamorphic rocks with minor basalt, gneiss, schist, granite, and conglomerate (Bureau of Geology and Mineral Resources of Sichuan Province 1991; see also Wu et al. 2009; Li et al. 2014) (Fig. 2). However, no direct sampling from local bedrock or plants provides a baseline for strontium. On the other hand, although the Sr isotope compositions of sediments are affected by more complex factors, other than the source bedrocks (Shao et al. 2014), Zhang et al.'s (2019) study of water samples from the rivers running through the Yanyuan Basin, where Guijiabao is located, reveals similar $^{87}Sr/^{86}Sr$ ratios (0.70797 and 0.70785) with our data. The data might provide a comparative basis for future studies of paleomobility in this mountainous area.

Can $\delta^{18}O$ values be a proxy for paleomobility?

The Chengdu Plain in the subtropical zone is a region heavily interwoven with water webs and is influenced by East Asian monsoons. Rivers flow all year round without much evaporation. It normally has more enriched $\delta^{18}O$ values in winter when precipitation is low. The terrain with basin effect also makes it easy to trap the heat and humidity, leading to relatively higher $\delta^{18}O$ values compared with the surrounding mountain areas even in summer. During the wet season (July–October), the $\delta^{18}O$ values vary between − 7.8 and − 9.1‰ (GNIP). However, the lowest values occur in January (avg. − 10.4‰), the coldest month (Xu et al. 2014), during which the temperature effect seemingly becomes obvious. These value ranges cover most Chengdu Plain samples (only three samples are slightly lower), as well as all the Yingpanshan samples. As a result, although researchers have attempted to use oxygen isotope ratio to detect human mobility, in this study, the $\delta^{18}O$ values do not appear to be sensitive enough to differentiate locals and non-locals, particularly those who lived along the Upper Min River and on the Chengdu Plain (the Lower Min River drainage). For instance, although samples from high elevations are supposed to have low $\delta^{18}O$ values due to the altitude effect (Dansgaard 1954, 1964), this was not observed in the data from the Yingpanshan site, which is at an elevation of 1500 m. Instead, all the Yingpanshan samples had the same $\delta^{18}O$ range as those from the Chengdu Plain, which is at an elevation of ca. 550 m. That is, the $\delta^{18}O$ value of the Upper Min River drainage is not significantly different from that of its lower watershed. In another study, water samples collected from the Min River also showed no correlation between $\delta^{18}O$ values and the altitudes from 700 to 2000 m above sea level (Xu et al. 2014). Another research shows that the $\delta^{18}O$ values remain similar even when the altitude exceeds 3000 m (Shi et al. 2017).

However, it seems that $\delta^{18}O$ values are still useful to distinguish people who came from different watersheds or from even higher locations if we take the Guijiabao data into account. The Guijiabao site is located at an elevation of 2400 m along the Yalong River, and the $\delta^{18}O$ values of the three Guijiabao people (− 14.0– − 12.3‰) are obviously lower than those of the people who lived along the Min River, though one Guijiabao data fell within the range of the data from the Chengdu Plain. These lower values may reflect either the different water systems or elevations, or both. More data is needed to clarify this.

Further to this, it appears that the $\delta^{18}O$ values also provide some interesting information regarding climate fluctuations. The $\delta^{18}O$ values of tooth samples from the Hongqiaocun site and the Zhixinjinshayuan locus were lower than those from the Yangguangdidai II, Jinniu Chengxiangyitihua 5B, and Xinyicun loci (Fig. 9). This may indicate that there was a cooler climate or a higher amount of precipitation during the late Baodun Period, when Hongqiaocun and Zhixinjinshayuan were inhabited, rather than in the Shi'erqiao Period, when the other three loci were occupied. The climate shift is also indicated by the stalagmites observed in the Dongge and Qixing caves in southwestern China (Cai et al. 2001; Dykoski et al. 2005). In fact, climate shift has been proposed as the reason for the abandonment of settlements in many regions around 2000 BC (e.g., Yasuda 2004:568). On the Chengdu Plain, flooding has been identified as an issue during the late Baodun Period (e.g., He 2015). For example, Jiang (2015) observed a layer of mud caused by flooding which interrupted the deposition in the fourth phase of the Baodun Period, although these floods might not necessarily have completely destroyed the settlements. It is therefore suggested in this paper that the $\delta^{18}O$ value of human tooth samples, when investigated in conjunction with other lines of evidence, can provide useful information in reconstructing the past climates of the Chengdu Plain.

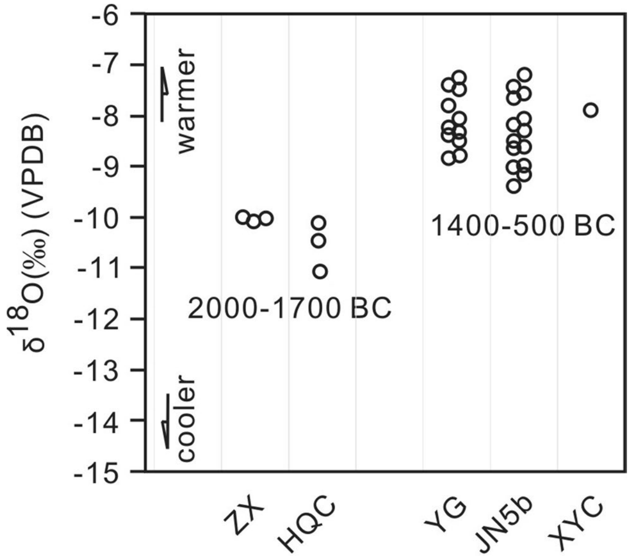

Fig. 9 A comparison of $\delta^{18}O$ values according to the ages of the sites for the human individuals on the Chengdu Plain

Conclusions

To the best of our knowledge, this is the first time that multi-isotope analyses have been carried out on archaeological tooth samples from Sichuan. There are some preliminary results that show great potential for further research. First, although it has been recognized in earlier studies that foxtail millet and broomcorn millet were important food sources consumed by the Yingpanshan and Guijiabao peoples, our study, combined with archaeobotanical and isotopic evidence, further suggests that such subsistence activities were practiced along the Upper Min River for a longer time than previously known, from the Neolithic Period to at least the Bronze Age.

Second, multi-isotopic analyses enable us to distinguish non-locals from locals more confidently. In this study, both the results of carbon and strontium isotope analyses indicate that the two Yingpanshan sacrificed individuals were non-locals, confirming our previous speculation (Lee et al. 2020a). Further to this, based on a series of comparisons of these isotopic measurements, it is very likely that the two individuals (M32, M40) grew up on the Chengdu Plain during the Shi'erqiao Period, when C_3-based foods contributed substantially to human diet, and moved to Yingpanshan later. The presence of Shi'erqiao pottery in the mountainous areas increases this likelihood. Given the geographical adjacency of the two regions, the presence of the Chengdu people along the Upper Min River should not be too surprising. However, besides material exchange, this is the first time that we have direct evidence from the human remains that they were non-locals coming from the Chengdu Plain. As non-locals, their unusual burial positions and the social meanings of these sacrificial burials and how these might inform the relationship between the lowland Chengdu Plain and its neighbors in the highlands should arouse our attention.

The role of Guijiabao in the proto Southern Silk Routes, parts of which used the valleys of Hengduan Mt., also deserves attention if we compare the pottery types and subsistence activities found in Guijiabao with those of other sites in the adjacent regions. It is very likely that the people who lived at the sites were in a location which was easy to accept cultural influences from different sources and also to pass them to other regions, such as Southeast Asia. With this combination of different lines of evidence, such as multiple isotopes discussed here, ecofact and archaeobotanical remains, and technological traditions, the complexity of regional interactions is revealed.

Third, although C_3-based foods, most likely rice, prevailed on the Chengdu Plain, two kinds of millets were also present as supplementary crops in the Jinsha site and Xinyicun locus. Both the archaeobotanical and isotopic evidence suggest that the inhabitants and their animal husbandry in these settlements on the Plain consumed small amounts of millets, yielding signals of C_4. Several individuals, who were possibly locals to the Chengdu Plain, with notably stronger C_4 signals, were nevertheless identified. These cases included both female and male. The reason for their high $\delta^{13}C$ values remains unclear given their burial and preservation conditions and requires further research. However, a bold speculation is suggested here that an increase in the consumption of millets on the Plain might be associated with poor rice harvest, which would be a sign of shortage in crops and might in turn cause malnutrition and some illnesses, which might be the case seen at Jinniu Chengxiangyitihua 5B and Yangguangdidai II. On the contrary, burial positions do not seem to matter in this regard. The individuals buried in the sideway flexed position previously thought unusual, did not seem to have divergent dietary patterns. Nor were they non-locals, based on the strontium analysis results. The strontium range that we suggest from the data used for this study is 0.71163–0.71394. This may represent the local bioavailable strontium baseline of the Chengdu Plain. Based on this baseline, only one possible non-local was identified. However, because of the poor preservation of the skeleton, we do not have more information regarding the burial. The wide range also cautions us that strontium, while useful in distinguishing special geological areas, might not be a very effective indicator for the Chengdu Plain. Those who stayed in the "local range" were not necessarily local people but only because they were indistinguishable from other local people, given current sampling methods and geological information. Additional evidence would be required to suggest the provenance of humans or animals.

Fourth, the $\delta^{18}O$ values of the tooth samples do not seem to be a sensitive enough proxy for the studies of paleomobility in the area of study, in particular, along the Min River drainage. However, the $\delta^{18}O$ values may provide useful information regarding the paleoclimate of the Chengdu Plain. The values suggest a cooler climate or flooding in the late Baodun Period, which coincides with the proposals of other studies. We expect to collect more data to understand the contribution of $\delta^{18}O$ values to paleoclimate studies, which might help us acquire a better picture of the environmental change during the Baodun Period and how this might relate to the decline of the society.

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Declarations

Conflict of interest The authors declare no competing interests.

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