**[Supplementary material]**

**Intermarriage and ancient polity alliances: isotopic evidence of cross-regional female exogamy during the Longshan period (2500–1900 BC)**

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**Comparison of burial style and funerary objects between Xiajin and other region cemeteries**

Similar to the Taosi site, the Xiajin cemetery consists of several foreign cultural elements in terms of burial customs and objects, with the jade *Yue (玉钺)* and the jade disc *(玉璧)* astwo primary funerary objects. The jade *Yue* was generally placed on the burial occupant's body as a symbol of military power, whereas the jade discwas worn on the wrist as a symbol of wealth (Figure 4.1). It is a burial custom that arose from the influence of the Dawenkou culture, not a local tradition of the Miaodigou II culture. In both the Dawenkou cemetery (Shandong & Jinan 1974) and the Jiaojia cemetery (Shandong & Chengziya 2019), high-ranking noble burials were commonly accompanied by the jade *Yue* and the jade disc, which were arranged the same way as in the Xiajin cemetery (Figure 4). Additionally, the wrists of several skeletons were found to be decorated with turquoise-inlaid bracelets in the Xiajin (Xiajin 1998) and Taosi cemeteries (CASS & Linfen 2015). Bracelets made from turquoise flakes, mussel shell grains and other stone fragments glued together with a black adhesive represent a fine example of Taosi culture craftsmanship (Figure 4.3). In addition, similar artifacts have been found at the Zongri site, Qinghai, on the Tibetan Plateau (Ge & Chen 1999) (Figure 4.4) and the Liangchengzhen site in coastal Shandong (Chinese-American Collabborative Team 2016). From the Late Neolithic to the Bronze Age, turquoise was prevalent in Gansu and Qinghai (Pang 2014) and was frequently glued using animal glue (Qin 2014). At sites such as Dianhe (Ningxia 1987), Xiahaishi (Gansu 2008), Yuanyangchi (Gansu & Wuwei 1974) and Liuwan (Qinghai & CASS 1984), turquoise-inlaid bracelets have also been identified (Figure 1). Accordingly, it may have been influenced by the Gansu-Qinghai region to use turquoise bracelets at the Xiajin site. Ringed shells from the Indian Ocean were found in the Taosi culture (﻿CASS 2003), and limestone imitation shell objects were also found in the Xiajin cemetery (Linfen & Shanxi 1999). In the third millennium BC, the most ringed shells were discovered in the Gansu-Qinghai region (Peng & Zhu 1999), so Taosi culture seashells were likely introduced from northwest China (highland).

According to burial objects, the Xiajin cemetery contains more cultural elements originating from the Dawenkou and Longshan cultures in east China. Only one type of pottery with painted vases of high-neck and fold-shoulders has been found in the Xiajin cemetery, both of which can be divided into two kinds of shapes, bulging belly (Figure 5.1) and curved belly (Figure 5.2). Both different shaped potteries are thought to be wine vessels originating from the Dawenkou culture, associated with the ones found in the Lingyanghe site in Shandong (Figure 5.9 & .10; Shandong *et al.* 1987). The most abundant burial objects in the Xiajin cemetery are jade and stone objects such as jade *Yues*, knives with double holes, *cong*-shaped bracelets, T-shaped bracelets and bracelets with repair. All of these objects were also found in the Dawenkou and Longshan cultures of Shandong (Figure 5; Wu *et al.* 2019). Several burials in Xiajin also contain the canine teeth of a boar (Shandong & Jinan 1974), and a similar burial custom was displayed more frequently in the Dawenkou Culture (Figure 5.8).

**Samples and methods**

Given the orderly arrangement of the tombs, with little intercutting, and the relative lack of pottery fine-scale stylistic changes, it is hard to judge the time span of the Xiajin cemetery by typology. To determine the date of tombs while avoiding the impact of a similar time of death, six human skeletons were selected from different sections of the cemetery and samples sent to Beijing University for radiocarbon analysis (Table S1).

Xiajin cemetery is located in the Linfen basin on a terrace along the east bank of the Fen River, where Quaternary loess is widely deposited. Geochemical studies have shown that the 87Sr/86Sr ratio of soluble carbonate in Quaternary loess in southern Shanxi Province is around 0.7110–0.7120 (Chen *et al.* 1997; Currell & Cartwright 2011). The strontium in the rivers flowing through the Quaternary Yellow Earth Belt and in the plants growing on the Quaternary loess is mainly derived from soluble carbonates in the loess, and the ratio of the strontium isotope is mainly restricted by the soluble carbonate in the loess. River water and plants are the main sources of strontium in the human body. Therefore, the 87Sr/86Sr ratio of human bones and teeth is also restricted by the soluble carbonate of loess and has a homogenous bioavailable 87Sr/86Sr range with little variation in 87Sr/86Sr (Zhao *et al.* 2011; Zhao *et al.* 2016a & b; Cao 2021).

The dental enamel of 67 adult human individuals, including 36 males and 31 females, from Xiajin cemetery was analysed for strontium, oxygen and carbon isotopes. We collected nine pig, one dog, one loess soil and five modern plant samples as references to determine the bioavailable 87Sr/86Sr around Xiajin's local area. To build the map of bioavailable 87Sr/86Sr ratios for related areas, we gathered reported 87Sr/86Sr ratios for plants, soils and animal and human bones at 37 sites. In addition, we also supplemented new 87Sr/86Sr ratio data of 48 samples, including ancient animals, human bones, modern plants and lake water from 18 sites (Figure 7; Table S3).

Sample pre-treatment varies depending on the material being analysed. Each enamel sample, weighing roughly 10–15mg, was cut from the tooth, and any adhering dentine and any visible dirt contamination were removed under a stereomicroscope. Plant samples were dried and ashed in a muffle furnace at 875°C, dissolved in hydrofluoric and nitric acid and evaporated to dryness under laminar flow conditions. Salt and lake water were dissolved in ultrapure water and were centrifuged, and the supernatant was evaporated to dryness in acid-cleaned Teflon beakers under a laminar flow hood (Hodell *et al*. 2004).

Following Sr separation routines, all samples were dissolved in ultrapure nitric acid in Teflon beakers on a hot plate at 120°C overnight. Strontium was purified using cation exchange chromatography with Eichrom Sr-specific resin (mesh 100–150µm) and nitric acid as the mobile phase. 87Sr/86Sr ratios were measured on the MC-ICP-MS (Neptune Plus) at the CAS Key Laboratory of Crust-Mantle Materials and Environments, School of Earth and Space Sciences, University of Science and Technology of China. The Sr carbonate standard NBS 987 yielded a value of 87Sr/86Sr=0.710248±0.000012 (2 sd, n = 100). All data are listed in Table S2 and Table S3.

For carbon and oxygen isotope measurements, powdered enamel samples were prepared in the Archaeometry Laboratory, University of Science and Technology of China, and then sent to the Isotope Laboratory of the Third Institute of Oceanography, State Oceanic Administration, for analysis. Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70°C in the headspace of the vial. The δ18O and δ13C values of tooth enamel carbonate were then measured using an automated carbonate preparation device (Gas Bench II) coupled to a gas-ratio mass spectrometer (Delta V, Thermo Scientific). The isotope ratio measurement is calibrated based on repeated measurements of IAEA-CO-1 and IAEA-CO-8, and the precisions are ± 0.2‰ for δ13C and ± 0.2‰ for δ18O (1 sd). All the detailed experimental procedures can be found in Wu *et al*. (2019a).

**Table S1. The AMS 14C dating of human bones from the Xiajin cemetery.\***

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Lab No. | Sample No. | 14C Age（BP） | Post-calibration Age | |
| 1σ (68.3%) | 2σ (95.4%) |
| BA192874 | ZY-9963（M48） | 3830±30 | 2340BC (10.2%) 2318BC  2306BC (58.0%) 2204BC | 2453BC (4.6%) 2419BC  2408BC (7.2%) 2374BC  2355BC (80.6%) 2197BC  2168BC (3.1%) 2148BC |
| BA192875 | ZY-9980（98M3） | 3780±30 | 2282BC (22.0%) 2251BC  2231BC (5.6%) 2220BC  2210BC (12.4%) 2192BC  2180BC (28.3%) 2142BC | 2296BC (91.2%) 2132BC  2085BC (4.2%) 2051BC |
| BA192876 | ZY-9987(M331) | 3745±50 | 2275BC (6.3%) 2256BC  2206BC (39.4%) 2122BC  2095BC (22.5%) 2039BC | 2336BC (0.5%) 2327BC  2299BC (93.5%) 2018BC  1996BC (1.5%) 1979BC |
| BA192877 | ZY-9988(M352) | 3810±25 | 2288BC (68.3%) 2204BC | 2342BC (85.8%) 2194BC  2176BC (9.6%) 2144BC |
| BA192878 | ZY-9997(M516) | 3835±25 | 2340BC (12.4%) 2318BC  2306BC (20.4%) 2274BC  2256BC (35.5%) 2206BC | 2452BC (4.1%) 2420BC  2406BC (7.2%) 2376BC  2352BC (84.2%) 2200BC |
| BA192879 | ZY-10000(M521) | 3885±25 | 2454BC (23.1%) 2417BC  2410BC (40.5%) 2341BC  2317BC (4.7%) 2308BC | 2464BC (95.4%) 2290BC |

\* 14C has a half-life of 5568 years and BP is years before 1950.

1 The calibration curve used is the IntCal13 atmospheric curve (Reimer *et al*. 2013).

2 The program used is OxCal v4.2.4 Bronk Ramsey (2013); r:5.

**Table S2. 87Sr/86Sr, δ13C and δ18O values of human tooth enamel from Xiajin cemetery (67 human individuals). LLM – lower left molar; LRM – lower right molar.**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Lab No. | Tomb No. | Gender | Sample | 87Sr/86Sr | SE (Standard Error)  \*10-6 | δ13C  VPDB‰ | δ18O  VPDB‰ | Burial gifts |
| ZY-9961 | M12 | Male | LLM1 | 0.711384 | 4 | -1.1 | -8.5 | Stone hairpin; Jade *Bi*, *Huang*; Bone ornament; Turquoise |
| ZY-9962 | M28 | Female | LRM1 | 0.711021 | 4 | -2.0 | -8.7 | Turquoise |
| ZY-9963 | M48 | Male | LLM1 | 0.711455 | 5 | -1.6 | -8.6 | Jade *Gui*, *Yue*, Handle |
| ZY-9964 | M49 | Male | LRM1 | 0.711637 | 4 | -1.4 | -8.5 | Jade *Yue*; Bone |
| ZY-9965 | M60 | Male | LLM3 | 0.711901 | 5 | -2.1 | -8.5 | Jade ornament; Stone arrowhead |
| ZY-9966 | M79 | Female | LRM1 | 0.711537 | 5 | -1.3 | -8.0 | Jade fragment |
| ZY-9967 | M83 | Female | LLM1 | 0.711544 | 4 | -4.3 | -6.6 | Jade awl; Bone hairpin |
| ZY-9968 | M85 | Male | LRM2 | 0.711418 | 3 | -1.5 | -8.9 | Pottery bottle |
| ZY-9969 | M161 | Female | LRM1 | 0.711213 | 4 | -1.7 | -7.9 | Stone shovel |
| ZY-9970 | M104 | Female | LLM1 | 0.711419 | 5 | -2.0 | -8.0 | Jade ornament, *Huang*; Wooden bracelet; Turquoise |
| ZY-9971 | M124 | Female | LRM1 | 0.711123 | 4 | -4.5 | -7.7 | Jade *Bi*, bead, ornament |
| ZY-9972 | M145 | Female | LRM1 | 0.711464 | 6 | -1.4 | -7.7 | Jade *Bi*; Tooth ornament |
| ZY-9973 | M152 | Female | LLM1 | 0.711605 | 4 | -1.9 | -8.4 | Shell ornament |
| ZY-9974 | M211 | Female | LRM1 | 0.711182 | 4 | -1.7 | -7.1 | Jade *Yue*; Stone *Bi* |
| ZY-9975 | M218 | Male | LLM1 | 0.711103 | 4 | -1.1 | -7.9 | Jade ornament, *Yue*, shovel; Stone bracelet |
| ZY-9976 | M229 | Male | LLM2 | 0.711883 | 7 | -0.7 | -7.8 | Jade bracelet |
| ZY-9977 | M235 | Female | LRM1 | 0.711053 | 3 | -1.3 | -6.9 | Jade *Cong*; Tooth ornaments |
| ZY-9978 | M240 | Female | LLM1 | 0.711399 | 4 | -1.8 | -8.0 | Pottery bottle |
| ZY-9979 | M241 | Male | LLM1 | 0.711219 | 5 | -2.3 | -8.0 | Jade ornament; Jade ornament; Stone *Yue*, *Bi*, shovel; Bone ornament, handle |
| ZY-9980 | 98M3 | Male | LLM1 | 0.711141 | 6 | -1.3 | -7.3 | Bone hairpin; Stone arrowhead, beads; Wooden kit |
| ZY-9981 | M259 | Female | LLM1 | 0.711291 | 4 | -1.1 | -8.1 | Bone hairpin |
| ZY-9982 | M268 | Male | LRM1 | 0.711169 | 8 | -1.5 | -7.3 | Jade *Bi*; Tooth ornaments |
| ZY-9983 | M269 | Female | LRM3 | 0.711512 | 4 | -2.0 | -10.1 | Jade *Yue*; Bone Hairpin |
| ZY-9984 | M273 | Female | LRM1 | 0.710496 | 4 | -2.0 | -7.5 | Jade bracelet; Tooth ornaments |
| ZY-9985 | M275 | Female | LRM3 | 0.71139 | 4 | -1.2 | -8.5 | Wooden bracelet |
| ZY-9986 | M299 | Female | M2 | 0.711376 | 4 | -1.2 | -7.6 | Turquoise |
| ZY-9987 | M331 | Female | LRM1 | 0.711286 | 4 | -1.3 | -9.5 | Bone hairpin |
| ZY-9988 | M352 | Female | LLM1 | 0.711359 | 4 | -1.0 | -8.2 | Stone bracelet |
| ZY-9989 | M372 | Male | LRM1 | 0.711247 | 5 | -2.3 | -8.9 | Jade *Bi*, ornament; Stone *Yue* |
| ZY-9990 | M374 | Male | M1 | 0.711282 | 5 | -1.2 | -8.2 | Jade *Yue* |
| ZY-9991 | M383 | Male | LLM1 | 0.711272 | 5 | -2.3 | -8.0 | Bone hairpins |
| ZY-9992 | 98M51 | Male | LLM1 | 0.711046 | 6 | -2.7 | -7.8 | Jade *Huang*, bracelet, Knife; Stone arrowhead, beads |
| ZY-9993 | 98M78 | Male | LLM2 | 0.711198 | 4 | -1.7 | -7.3 | Stone beads, ornament |
| ZY-9994 | M410 | Male | LLM3 | 0.711268 | 5 | -1.0 | -9.4 | Jade *Yue* |
| ZY-9995 | M474 | Female | LLM1 | 0.711432 | 4 | -1.6 | -8.5 | Bone hairpin |
| ZY-9996 | M477 | Male | LRM1 | 0.711213 | 5 | -2.9 | -7.7 | Jade *Yue* |
| ZY-9997 | M516 | Male | LRM1 | 0.711233 | 4 | -1.2 | -7.2 | Stone bracelet; Jade *Yue* |
| ZY-9998 | M518 | Male | LLM1 | 0.711162 | 6 | -1.6 | -8.2 | Jade *Yue* |
| ZY-9999 | M519 | Male | LRM1 | 0.711166 | 4 | -1.7 | -8.2 | Jade *Yue* |
| ZY-10000 | M521 | Female | LLM1 | 0.712098 | 5 | -1.5 | -8.4 | None |
| ZY-11481 | M5 | Female | LRM1 | 0.711216 | 5 | -1.83 | -8.3 | Stone ornament with one hole |
| ZY-11482 | M329 | Female | LLM2 | 0.711893 | 5 | -2.12 | -9.6 | Bone hairpin |
| ZY-11483 | M386 | Female | LLM2 | 0.711580 | 4 | -1.37 | -9.0 | None |
| ZY-11484 | M141 | Male | LRM1 | 0.711273 | 4 | -1.52 | -8.9 | Tooth ornament；Stone *Bi* |
| ZY-11485 | M151 | Male | LLM1 | 0.711137 | 5 | -2.55 | -8.4 | Shell ornament；Bone hairpin；Stone piece |
| ZY-11486 | M212 | Male | LLM1 | 0.711205 | 6 | -1.75 | -8.8 | Tooth ornament；Stone arrowhead；Stone *Bi* |
| ZY-11487 | M363 | Female | LLM1 | 0.711622 | 8 | -1.58 | -7.5 | None |
| ZY-11488 | M263 | Male | LLM1 | 0.711566 | 4 | -1.75 | -8.4 | Stone *Yue* |
| ZY-11489 | M286 | Female | LLM1 | 0.711327 | 5 | -1.32 | -8.2 | Bone hairpin |
| ZY-11490 | M289 | Female | LRM1 | 0.711448 | 5 | -2.85 | -8.2 | Stone arrowhead |
| ZY-11491 | M301 | Male | LRM1 | 0.711580 | 6 | -1.79 | -8.9 | Stone arrowhead；Bone arrowhead |
| ZY-11492 | M302 | Female | LLM1 | 0.711478 | 5 | -2.17 | -8.0 | Bone hairpin |
| ZY-11493 | M308 | Female | LLM2 | 0.713198 | 4 | -1.16 | -9.0 | Bone hairpin |
| ZY-11494 | M311 | Female | LLM2 | 0.710936 | 5 | -1.13 | -8.7 | Bone hairpin |
| ZY-11495 | M319 | Female | M1 | 0.711480 | 5 | -1.46 | -8.5 | Bone hairpin |
| ZY-11496 | M428 | Male | M1 | 0.711374 | 5 | -1.61 | -8.6 | Stone *Yue* |
| ZY-11497 | M332 | Male | M1 | 0.711299 | 5 | -1.42 | -8.4 | Stone *Yue* |
| ZY-11498 | M335 | Male | LLM1 | 0.711172 | 5 | -2.37 | -8.6 | Stone *Yue* |
| ZY-11500 | M385 | Male | LRM1 | 0.711357 | 6 | -1.88 | -8.3 | Stone Blades with double holes |
| ZY-11501 | M144 | Male | LRM1 | 0.711672 | 5 | -1.72 | -8.3 | Stone hairpin；Stone ornament |
| ZY-11502 | M155 | Male | LLM1 | 0.711209 | 5 | -1.70 | -8.6 | None |
| ZY-11503 | M162 | Female | LLM1 | 0.711187 | 5 | -1.43 | -7.9 | None |
| ZY-11504 | M173 | Male | LLM1 | 0.711387 | 5 | -1.50 | -7.5 | None |
| ZY-11505 | M237 | Male | LLM1 | 0.711135 | 5 | -1.69 | -7.7 | None |
| ZY-11506 | M257 | Male | LRM1 | 0.711187 | 5 | -1.40 | -7.8 | None |
| ZY-11507 | M272 | Male | LLM1 | 0.711329 | 4 | -2.17 | -8.5 | None |
| ZY-11508 | M295 | Male | LLM1 | 0.711200 | 5 | -1.96 | -8.1 | Stone hairpin |

**Table S3. Bioavailable 87Sr/86Sr ratios in this study.**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Site No. | Site | Lab No. | Sample | 87Sr/86Sr ratio  or range | SE \*10-6 | Data sources |
| 1 | **Linfen**  **Xiajin** | **ZY-10522** | **Plant** | **0.711235** | **6** | **This study** |
| **ZY-10523** | **0.711312** | **5** |
| **ZY-10524** | **0.711307** | **8** |
| **ZY-10525** | **0.711289** | **7** |
| **ZY-10526** | **0.711356** | **8** |
| **ZY-11499** | **Pig enamel** | **0.711311** | **5** |
| **ZY-11509** | **Loess** | **0.711429** | **4** |
| 2 | **Xiangfen**  **Taosi** | **ZY-11246** | **Pig enamel** | **0.711190** | **7** | **This study** |
| **ZY-11247** | **Pig enamel** | **0.711202** | **7** |
| **ZY-11248** | **Pig enamel** | **0.711117** | **5** |
| **ZY-11249** | **Dog enamel** | **0.711125** | **7** |
|  | Pig enamel | 0.711282 | 19 | Zhao *et al*. 2011; Zhao & Fang 2014 |
|  | Pig enamel | 0.711126 | 11 |
|  | Pig enamel | 0.711107 | 15 |
|  | Pig enamel | 0.711145 | 11 |
|  | Pig enamel | 0.711235 | 10 |
|  | Human and animal enamel | 0.7110–0.7117 | 33 |
| 3 | **Jiangxian**  **Zhoujiazhuang** | **ZY-9420** | **Animal enamel** | **0.711403** | **7** | **This study** |
| **ZY-9422** | **0.711425** | **9** |
| **ZY-9423** | **0.711562** | **7** |
| **ZY-9424** | **0.711609** | **8** |
| **ZY-9425** | **0.711628** | **8** |
| **ZY-9426** | **0.711499** | **7** |
| 4 | Ruicheng  Qingliangsi |  | Human and animal enamel; plant | 0.7112–0.7118  (n = 31) |  | Zhao *et al*. 2016a; Wu *et al*. 2019b |
| 5 | Fushan  Qiaobei |  | Animal enamel | 0.711372–0.711392  (n = 3) |  | Cao 2021 |
| 6 | Xinzhou  Liugou |  | Animal enamel | 0.711323–0.711571  (n = 4) |  | Cao 2021 |
| 7 | Lingshi  Jingjie |  | Animal enamel | 0.711040–0.711357  (n = 2) |  | Cao 2021 |
| 8 | Shilou |  | Animal enamel | 0.711118–0.711194  (n = 3) |  | Cao 2021 |
| 9 | Liulin  Gaohong |  | Animal enamel | 0.711184–0.711237  (n = 3) |  | Cao 2021 |
| 10 | Qingjian  Lijiaya |  | Animal enamel | 0.711280 |  | Cao 2021 |
| 11 | Qingjian  Xinzhuang |  | Animal enamel | 0.711153 |  | Cao 2021 |
| 12 | Ansai  Xiwaqu |  | Animal enamel | 0.711251 |  | Cao 2021 |
| 13 | Shenmu  Dabaodang |  | Animal enamel | 0.711036–0.711302  (n = 2) |  | Cao 2021 |
| 14 | Zhukaigou |  | Animal enamel | 0.711075–0.711198  (n = 2) |  | Cao 2021 |
| 15 | Shenmu  Shimao |  | Animal enamel | 0.7110–0.7113  (n = 24) |  | Zhao *et al*. 2016a |
| 16 | Yangling |  | Soil extracts | 0.7115–0.7117  (n = 18) |  | Liu *et al*. 2016 |
| 17 | Chunhua  Zaoshugounao |  | Human and animal enamel | 0.7110–0.7117  (n = 32) |  | Lan 2017 |
| 18 | Xian’an  Laoniupo |  | Animal enamel | 0.711369–0.711616  (n = 4) |  | Cao 2021 |
| 19 | Hancheng  Liangdaicun |  | Human bone and enamel | 0.7111–0.7120  (n = 33) |  | Chen 2012 |
| 20 | Yanshi  Erlitou |  | Animal enamel | 0.7117–0.7126  (n = 17) |  | Zhao 2012 |
| 21 | Xinzheng  Wangjinglou |  | Animal enamel | 0.7113–0.7120  (n = 15) |  | Zhao 2018 |
| 22 | Xinxiang |  | Soil extracts | 0.7116–0.7121  (n = 18) |  | Liu *et al*. 2016 |
| 23 | Anyang  Xiaomingtun |  | Animal enamel | 0.7113–0.7117  (n = 10) |  | Zhao *et al*. 2015 |
| 24 | Cixian  Nancheng |  | Animal enamel | 0.7116–0.7120  (n = 5) |  | Hou *et al*. 2021 |
| 25 | Shijiazhuang |  | Soil extracts | 0.7127–0.7131  (n = 18) |  | Liu *et al*. 2016 |
| 26 | Zhangqiu  Jiaojia |  | Human and animal enamel | 0.7110–0.7117  (n = 40) |  | Fang 2018 |
| 27 | Zouping  Dinggong |  | Animal bone and enamel | 0.7110–0.7115  (n = 16) |  | Wu *et al*. 2018 |
| 28 | Xichuan  Xiawanggang |  | Human and animal enamel | 0.7124–0.7127  (n = 29) |  | Zhao 2020 |
| 29 | Yuzhou  Wadian |  | Human and animal enamel | 0.7120–0.7128  (n = 16) |  | Zhao 2012; Zhao & Fang 2014 |
| 30 | Wuyang  Jiahu |  | Human and animal enamel | 0.7122–0.7126  (n = 26) |  | Yin *et al*. 2008 |
| 31 | Tai’an  Dawenkou |  | Animal enamel | 0.7137–0.7146 (n = 5) |  | Fang 2018 |
| 32 | Sishui  Yinjiacheng |  | Human bone | 0.7123–0.7127  (n = 10) |  | Wu *et al*. 2019b |
| 33 | **Linyi**  **Houyangguanzhuang** | **ZY-9514** | **Animal enamel** | **0.7147020** | **6** | **This study** |
| **ZY-9516** | **0.7126640** | **6** |
| 34 | **Xiaoxian**  **Jinzhai** | **ZY-10196** | **Human enamel** | **0.712398** | **7** | **This study** |
| 35 | Hanshan  Lingjiatan |  | Animal enamel and bone | 0.7120–0.7126  (n = 12) |  | Zhao *et al*. 2019 |
| 36 | Minhe  Lajia |  | Human enamel and bone; Animal enamel | 0.7108–0.7110  (n = 49) |  | Zhao *et al*. 2016b |
| 37 | Zhangye  Xichengyi |  | Human bone and enamel | 0.7124–0.7125  (n = 4) |  | Zhao 2012 |
| 38 | Shanghai  Guangfulin |  | Modern plant | 0.7092–0.7108 |  | Zhejiang & Jiaxing 2019 2019 |
| 39 | Jiaxing  Majiabang |  | Human enamel | 0.7093–0.7102  (n = 66) |  | Zhejiang Province *et al*. 2019 |
| 40 | Xinghua |  | Modern animal | 0.7106–0.7107  (n = 9) |  | Yin *et al*. 2020 |
| 41 | **Tengzhou**  **Xigongqiao** | **ZY-10435** | **Animal enamel** | **0.713924** | **11** | **This study** |
| **ZY-10437** | **0.714296** | **8** |
| 42 | **Bengbu** | **ZY-10817** | **Modern plant** | **0.712654** | **5** | **This study** |
| **ZY-10815** | **0.712257** | **5** |
| **ZY-10816** | **0.712369** | **5** |
| 43 | **Guzhen**  **Gaixia** | **ZY-10819** | **Modern plant** | **0.712155** | **5** | **This study** |
| **ZY-10814** | **0.712454** | **5** |
| 44 | **Rizhao Liangchengzhen** | **ZY-9490** | **Animal enamel** | **0.710455** | **5** | **This study** |
| **ZY-9491** | **Animal enamel** | **0.710772** | **6** |
| **ZY-10739** | **Modern plant** | **0.710925** | **7** |
| 45 | **Rizhao**  **Sujiacun** | **ZY-11147** | **Human enamel** | **0.710957** | **7** | **This study** |
| 46 | **Jimo**  **Beiqian** | **ZY-9530** | **Animal enamel** | **0.710069** | **5** | **This study** |
| **ZY-9531** | **0.710758** | **4** |
| **ZY-9532** | **0.709845** | **6** |
| **ZY-9533** | **0.710915** | **5** |
| **ZY-9534** | **0.710933** | **5** |
| 47 | **Fuyang**  **Yuejiahu** | **ZY-10642** | **Animal enamel** | **0.712464** | **7** | **This study** |
| 48 | **Ruzhou**  **Xiaoyuzhuang** | **ZY-10901** | **Modern plant** | **0.712663** | **7** | **This study** |
| 49 | **Lingbao**  **Jiaocun** | **ZY-10905** | **Modern plant** | **0.711764** | **6** | **This study** |
| 50 | **Salt Lake** | **ZY-9377** | **Modern plant** | **0.712469** | **8** | **This study** |
| **ZY-9378** | **Modern plant** | **0.712339** | **8** |
| **ZY-9379** | **Modern plant** | **0.713027** | **9** |
| **ZY-9381** | **Modern plant** | **0.712432** | **8** |
| **ZY-9380** | **Modern plant** | **0.712748** | **8** |
| **ZY-9382** | **Modern plant** | **0.713037** | **9** |
| **ZY-9383** | **Modern plant** | **0.712421** | **6** |
| **ZY-9405** | **Modern plant** | **0.712683** | **9** |
| **ZY-9384** | **Modern plant** | **0.712602** | **8** |
| **ZY-9385** | **Modern plant** | **0.713500** | **9** |
| **ZY-9406** | **Salt Lake water** | **0.712989** | **8** |
| 51 | **Xiaxian**  **Dongxiafeng** | **ZY-11397** | **Modern plant** | **0.712653** | **7** | **This study** |
| **ZY-11398** | **Modern plant** | **0.712919** | **8** |
| **ZY-11400** | **Modern plant** | **0.711976** | **8** |
| 52 | **Qinshui**  **Baliping** | **ZY-11401** | **Modern plant** | **0.712343** | **8** | **This study** |
| **ZY-11402** | **Modern plant** | **0.711977** | **7** |
| **ZY-11403** | **Modern plant** | **0.712622** | **6** |
| **ZY-11404** | **Modern plant** | **0.712282** | **7** |
| **ZY-11405** | **Modern plant** | **0.712395** | **7** |
| 53 | **Dingtao Wangzhuang** | **ZY-10784** | **Modern plant** | **0.7116729** | **7** | **This study** |
| 54 | Zhengzhou  Shang city |  | Pig enamel | 0.711724 | 14 | Fang *et al*. 2022; Fang 2016 |
|  | Pig enamel | 0.711718 | 13 |
|  | Pig enamel | 0.711637 | 15 |
|  | Pig enamel | 0.711724 | 19 |
|  | Pig enamel | 0.711878 | 11 |
|  | Pig enamel | 0.71177 | 20 |
|  | Pig enamel | 0.711665 | 13 |
|  | Pig enamel | 0.711762 | 15 |
|  | Pig enamel | 0.711818 | 21 |
|  | Pig enamel | 0.711751 | 17 |
| 55 | Daxingzhuang |  | Ancient animal enamel | 0.711082–0.711596  (n = 13) |  | Fang *et al*. 2022; Fang 2016 |
| 56 | Jiaozuo  Fucheng |  | Ancient  animals  enamel | 0.710846–0.711340 (n = 9) |  | Fang *et al.* 2022; Fang 2016 |
| 57 | Anyang  Zhangdeng |  | Pig enamel | 0.711591–0.712219  (n = 8) |  | Fang *et al*. 2022; Fang 2016 |

**References**

Bronk Ramsey, C. 2021. OxCal v4.4.4 Available at: https://c14.arch.ox.ac.uk/oxcal.html

Cao, D. Z. 2021. *The loess highland in a trading network (1300–1050 BC)*.Beijing: Beijing University Press.

Cass (Institute of Archaeology, Chinese Academy of Social Sciences). 2003. Tombs of the Middle Taosi Culture discovered on the Taosi City-site. *Archaeology* 9: 771–74.

Cass & Linfen (Institute of Archaeology, Chinese Academy of Social Sciences & Linfen Cultural Heritage Administration, Shanxi Province). 2015. *Taosi site archaeological excavation reports 1978–1985*.Beijing: Heritage Press.

Chen, Jun., Gang Qiu & JieDong Yang. 1997. Sr isotopic composition of loess carbonates with primary and secondary carbonate identification. *Advances in Natural Sciences* 6: 93–96.

Chen, X. 2012. A study of the osteochemical characteristics of human bones from the Western Zhou period excavated from the Rui State Cemetery at Liangdaicun. Masters dissertation. M.S. Northwestern University.

Chinese-American Collaborative Team. 2016. *Liangchengzhen:1998–2001 Excavation Report*. Beijing: Cultural Relics Press.

Currell, M.J. & I. Cartwright. 2011. Major-ion chemistry, δ13C and 87Sr/86Sr as indicators of hydrochemical evolution and sources of salinity in groundwater in the Yuncheng Basin, China. *Hydrogeology Journal* 19: 835–50. https://doi.org/10.1007/s10040-011-0721-6

Fang, F. 2016. Indentity and source of the skulls unearthed from skulls ditch, Zhengzhou Shang City. Unpublished PhD dissertation, University of Science and Technology of China.

Fang, F., J. Liao, X. Zeng & J. Zhang. 2022. The truth of unusual deaths under military expansion: Evidence from the stable isotopes of a human skull ditch in the capital city of the early Shang Dynasty. *Genes* 13: 2077. https://doi.org/10.3390/genes13112077

Fang, S.Y. 2018. Strontium isotope analysis of human migrations of Jiaojia site. Masters dissertation. M.S. Jinan: Shandong University.

Gansu & Wuwei (Gansu Museum, Wuwei Cultural Heritage General Investigation Team). 1974. Excavation of the Neolithic cemetery at Yuanyangchi, Yongchang. *(Kaogu) Archaeology* 5: 299–308.

Gansu (Gansu Provincial Institute of Archaeology). 2008. Lanzhou Honggu Xiahaishi.Beijing: Science Press.

Ge, S.B. & H.H. Chen. 1999. The Zongri Site—A selection of artifacts and commentary.Chengdu: Sichuan Science and Technology Press.

Hodell, D.A., R.L. Quinn, M. Brenner & G. Kamenov. 2004. Spatial variation of strontium isotopes (87Sr/86Sr) in the Maya region: a tool for tracking ancient human migration. *Journal of Archaeological Science* 31: 585–601. https://doi.org/10.1016/j.jas.2003.10.009

Hou, L.L., D. Wei & P.R. Michael. 2021. Diversification origins of the populations from the Nancheng cemetery during proto-Shang culture (ca. 2000~1600BC) evidenced by strontium isotope analysis. *Quaternary Sciences* 41: 235–46.

Lan, D. 2017. Isotope analysis on human and animal bone unearthed from Zaoshugounao site in Chunhua, Shaanxi Province. Masters dissertation. M.S. Xi’an: Northwestern University.

Linfen & Shanxi (Linfen Administration Cultural Bureau, Shanxi Province & Shanxi Archaeological Team, Institute of Archaeology, Chinese Academy of Social Sciences). 1999. Excavations of the Taosi Culture cemetery at Xiajin village, Linfen, Shanxi. *Acta Archaeologica Sinica* 4: 459–86.

Liu, H.Y. *et al.* 2016. Combination of the 87Sr/86Sr ratio and light stable isotopic values (δ13C, δ15N, and δD) for identifying the geographical origin of winter wheat in China. *Food chemistry* 212: 367–373. https://doi.org/10.1016/j.foodchem.2016.06.002

Ningxia (Ningxia Institute of Archaeology). 1987. Ningxia Guyuan Dianhe Qijia culture burial mounds cleaning brief. *Kaogu (Archaeology*) 8: 673–77.

Pang, X.X. 2014. The studies on the turquoise objects of the Neolithic age unearthed in China. *Acta Archaeologica Sinica* 2: 139–68.

Peng, K. & Y.S. Zhu. 1999. New probe into the sources of the cowries used in ancient China. *Papers on Chinese Archaeology No.12*.

Qin, X.L. 2014. Ancient Chinese marquetry and turquoise ornaments. Capitals of Xia and Shang and Culture 2.Beijing: China Social Science Press.

Qinghai & CASS (Qinghai Provincial Institute of Archaeology & Institute of Archaeology, Chinese Academy of Social Sciences). 1984. Qinghai Liuwan-Liuwan primitive society cemetery in Ledu. Beijing: Cultural Relics Press.

Reimer, P.J. *et al*. 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62: 725–57. https://doi.org/10.1017/RDC.2020.41

Shandong & Chengziya. (Shandong University Department of Archaeology and Cultural Relics Museum & Chengziya Museum). 2019. The excavation of the large burials of the Jiaojia site in Zhangqiu district, Jinan, Shandong: a preliminary report of the 2016-2017 seasons. *Kaogu (Archaeology)* 12: 20–48.

Shandong & Jinan (Shandong Provincial Cultural Heritage Administration & Jinan Museum). 1974. Report on the excavation of a Neolithic burial at Dawenkou.Beijing: Cultural Relics Press.

Shandong, Shandong & Juxian. (Shandong Provincial Institute of Archaeology, Shandong Museum & Juxian Cultural Heritage Administration).1987. Excavation brief of the Dawenkou culture burials at Lingyang river, Juxian, Shandong. *Prehistory* 3: 62–82.

Wu, X.T., Hein, A., Zhang, X., *et al*. 2019a. Resettlement strategies and Han imperial expansion into southwest China: a multimethod approach to colonialism and migration. *Archaeological and Anthropological Sciences* 11: 6751–81. https://doi.org/10.1007/s12520-019-00938-w

Wu, X.T., Zhang, X.X., Jin, Z.Y., *et al*. 2019b. Strontium isotope analysis of Yangtze alligator remains from Late Neolithic North China. *Archaeological and Anthropological Sciences* 11: 1049–58. https://doi.org/10.1007/s12520-017-0589-z

Wu, X.T. *et al*. 2018. The Strontium isotope analysis of the aquatic animal resources of the dinggong site. *Kaogu (Archaeology)* 1: 111–18.

Xiajin (Xiajin Archaeological Team, Institute of Archaeology, Chinese Academy of Social Sciences).1998. Excavation of the Xiajin cemetery at Linfen in Shanxi. *Wenwu (Cultural Relics)* 12: 4–13.

Yin, R.C., J.Z. Zhang & X.Y. Yang. 2008. Preliminary study of prehistoric human migration based on Sr isotope analysis from Jiahu relics. *Quaternary Sciences* 28: 50–57.

Yin, H.M., F. Huang, J. Shen & H.M. Yu. 2020. Using Sr isotopes to trace the geographic origins of Chinese mitten crabs. *Acta Geochimica* 39: 326–36. https://doi.org/10.1007/s11631-020-00407-5

Zhao, C.Y. 2012. Strontium isotope ratio analysis of human remains excavated from the Heishui State site, Zhangye, Gansu. *Proceedings of the 13th Annual Chinese Vertebrate Zoology Conference*.Beijing: Ocean Press.

– 2018. Tracing provence of cattle and sheep in district of mount Songshan in Erlitou culture period—Taking Erlitou site and Wangjinglou site as examples. *Huaxia kaogu (Huaxia Archaeology)* 6: 77–84.

– 2020. Strontium isotope ratio analysis of human and animal remains from the Xichuan Xiawanggang site. Xichuan Xiawanggang.Beijing: Science Press.

Zhao, C.Y. & Y.M. Fang. 2014. Strontium isotopic ratio analysis of the enamel of human teeth from Yuzhou Wadian site. *Huaxia kaogu (Huaxia Archaeology)* 3: 123–27.

Zhao, C.Y., S.H. Hu, Z.Y. Sun, J. Shao & M.M. Yang. 2016a. Strontium isotopic analysis of teeth dental tissues from the Houyangwan locus at the Shimao site in Shenmu, Shaanxi. *Kaogu yu wenwu (Archaeology and Cultural Relics)* 4: 128–33.

Zhao, C.Y., Z.P. Li & J. Yuan. 2015. The ratio analysis of strontium isotope to the tooth enamel of horse and pig unearthed in Yin Ruins, Anyang, Henan Province. *Nanfang wenwu* (*Cultural Relics in Southern China)* 3: 77–80.

Zhao, C.Y., P. Lv & Z. Shuo. 2019. Strontium isotope ratio analysis of some animal remains unearthed from the Lingjiatan and Weigang sites in Hanshan County, Anhui Province. *Nanfang wenwu* (*Cultural Relics in Southern China)* 2: 184–90.

Zhao, C.Y., M.H. Wang & M.L. Ye. 2016b. Strontium isotope analysis of human teeth and bones from the Lajia site in Qinghai province. *Acta Anthropologica Sinica* 35: 212–22.

Zhao, C.Y., J. Yuan & N. He. 2011. Strontium isotope analysis of archaeological fauna from the Taosi site, Xiangfen, Shanxi. *Quaternary Sciences* 31: 22–28.

Zhejiang & Jiaxing (Zhejiang Provincial Institute of Archaeology & Jiaxing Museum). 2019. Majiabang.Beijing: Cultural Relics Press.