# SCIENTIFIC ANALYSES ON TECHNICAL CERAMICS FROM YAOHEYUAN, NINGXIA. THE APPROACH OF UNDERSTANDING TECHNOLOGICAL CHOICES IN A REMOTE BRONZE-CASTING WORKSHOP

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## 1. Introduction

The newly discovered site Yaoheyuan姚河塬, located in Pengyang, Ningxia province (Figure 1, highlighted in green), represents the westernmost territory of the Western Zhou (1046-771 BCE)[2] dominion. Excavations have unveiled a complex array of structures, including walls, houses, tombs, palaces, and workshops. Scholars have identified this site as the capital of the state of Huo获, and was active throughout the Western Zhou period[3].

According to the excavators, the casting workshop (Figure 2; around 4200 m[2] has currently been excavated) sits on the north, adjacent to the ceramic workshop. Over 1000 pieces of technical ceramics have been found at the site, predominantly consisting of moulds for tools and weapons, and those for ritual vessels are notably scarce (Ningxia ICRA *et al.*, 2021).
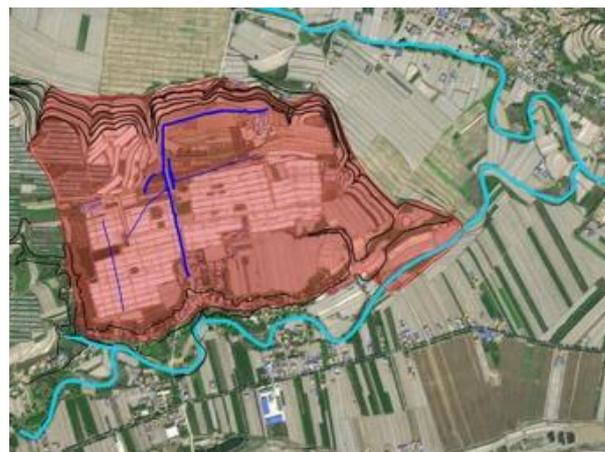


*Figure 1. Site location and aerial view.*

Piece-mould Casting Technology泥质块范法, a method employed by ancient Chinese craftsmen, is in contrast with the lost wax technique used widely by other ancient cultures. This traditional Chinese approach is based on the use of loess (Pope *et al.*, 1967). Various types of loess were unearthed and subjected to a series of processes, including selection, levigation, tempering, pugging, and staling (Su *et al.,* 1995). During these processes, most of the clay and larger silts were deliberately removed, resulting in a well-sorted silt matrix. With this refined material, craftsmen formed models, moulds, and cores. These separate pieces were later assembled for casting. This method highlights the unique ingenuity of ancient Chinese metallurgical practices.
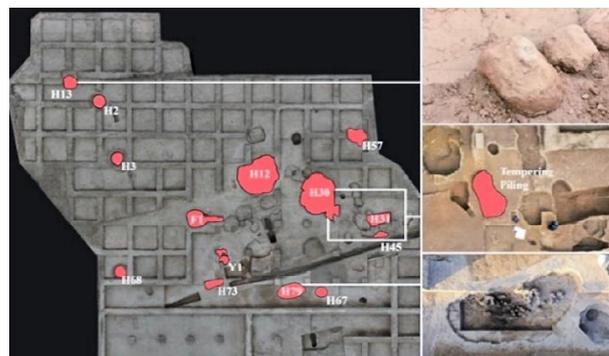


*Figure 2. Bronze casting workshop, with pits where samples used in this article were excavated.*

To date, archaeologists have excavated numerous bronze casting sites, which have also raised many questions regarding bronze casting techniques (Su 2020). As research progresses, scholars have found that the production technology of bronze casting moulds and cores is not as either uniform or complex as previously thought, as the Yaoheyuan foundry showed. The raw materials are usually local soil taken near the casting site, and craftsmen all around China still managed to cast bronzes. With these different raw

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[2] Mainly in Shaanxi, Shanxi, and Henan province.

[3] Relics from late Western Zhou period are relatively fewer.

materials, where lies the commonality? Additionally, some cores have grogs with elemental compositions differing from local materials. These grogs could be evidence of import. The exact spread and evolution of bronze casting technology, as well as the technology chosen by craftsmen for mould-making, are the questions that need to be addressed. By analysing the Yaoheyuan site, we may gain a better understanding of ancient Chinese bronze casting techniques.

## 2. Samples and methods

### 2.1. Description
Thirty-four samples (Figure 3) were provided by the archaeologists: these include seven processed soils, 20 pieces of technical ceramics, five smelting remains and two pottery sherds. Most samples came from six pits: H2 (No.1-16), H3 (No.17-20), H13 (No.21-23), H30 (No.24), H31 (No.25-26), and Y1 (No.27-30)[4]. Other samples were also found at the site. Fifty-five soil samples were collected from these pits and various locations within the site at different depths.



*Figure 3. Samples discussed in the text.*

### 2.2. Methods
Fifty-two thin sections were made for petrographic analysis; photos were taken with Leica DM 750P. Each section was also polished for SEM-EDX analysis. High-magnification SEM-BSE imaging was used to distinguish coatings, layers, contamination, and usage. The analyses were conducted with Thermo Scientific Quattro S coupled with Bruker QUANTAX X energy dispersive spectrometer, running at a working distance of 15mm under 15kV for 180s. CT scanning was used on one sample, with Yxlon's micro-focus X-ray system, running under 170kV and 0.34mA, with 0.065mm resolution.

## 3. Results

### 3.1. Macroscopic observation
During the sampling procedure, some interesting phenomena were revealed:

1. H2①:116 and H2②:79 are two used cores, both were porous: their structure suggests that they were probably produced from a mould.[5] H2①:103 and H2②:105 both have small cracks, which are possibly formed with pressing actions, suggesting that these samples were from moulds. H2⑤:9 have a casting seam (normally seen on cast bronzes) on one surface, which is evidence of a mould-making process. This sample has an unusual T-shaped structure, some of the surfaces were burnt. It could be a core or model of *xia* (linchpin).

In summary these four items might have their own mould or "core box", just like the ones used for making ceramic amulets.[6]

2. 13 samples' surfaces are different from the layer underneath, suggesting a different treatment. After sectioning the samples, six of them revealed different surface treatments, including three types: H2①:103 and H2③:7 were coated, H2②:81 and H13③:1 have a very thick layer, H2①:55 and H2⑤:4 were layered with a black thick black surface.

3. Some fragments of snail shells were found in the samples, and some were quite large. It suggests that the raw material is not, or poorly, levigated.

### 3.2. Petrographic analysis
#### 3.2.1. Fabric groups
In this article, we focus only on the major differences. Samples from Yaoheyuan share a similar fabric, ten of them have been used. Based on the colour and inclusions, these samples could be classified into four groups. All samples have a calcareous fabric with 20-30 % well-sorted quartz.

*Group 1* (H2①:103, H2①:116, and H2②:79) is porous with a dark brown fabric (Figure 4(a)). The burnt matrix has abundant cryptocrystalline calcite, which is very different from others. The similar fabric could also be seen at some surfaces of the moulds, e.g. H2⑤:4.

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[4] Seven processed soils were found piled up in pits and categorised by the archaeologists as "raw materials". These are different from 55 raw soil samples. The numbers used here correspond to the sample numbers, which can be seen in Table 1.

[5] Simulation of this technique see She *et al.* 2012.
[6] Discussion on core box see Dong, 2011, and for more similar examples see The Institute of Archaeology, CASS, 2020.
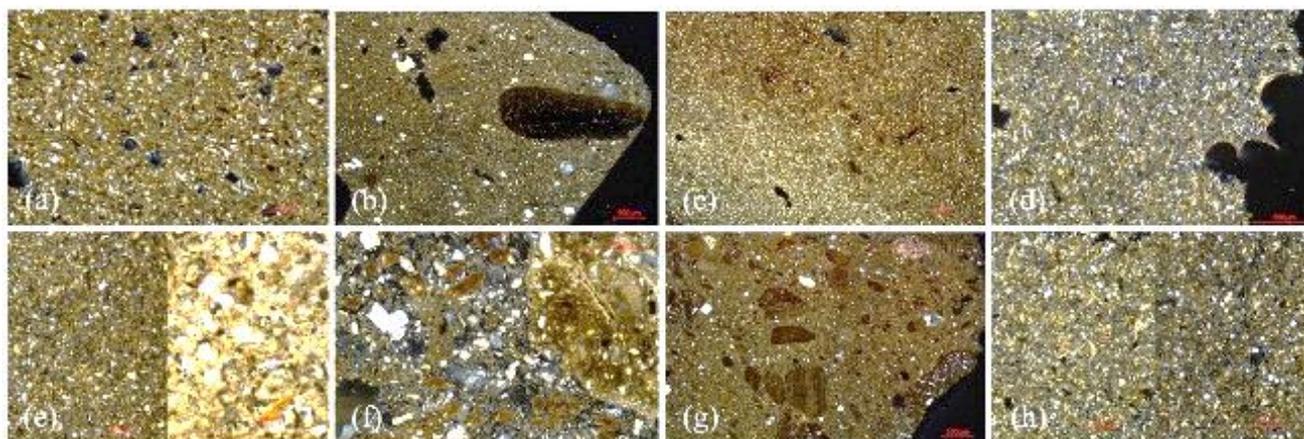
*Figure 4. Petrographic Photos. (a) H2①:103, Group 1; (b) H31②:9, Group 2; (c) H2⑤:4, Group 3; (d) H2①:126, one sub group in Group 4; (e) H2②:81, one sub group in Group 4; (f) Y1筛出采集遗物, Tempers piling; (g) Pottery sherd; (h) Split image: left is raw soil sample and right, burnt soil.*

*Group 2* (H31②:9), is the only one to be tempered (Figure 4(b)). The tempering has similar size and type as those in ceramics (Figure 4(g)).

*Group 3* (H2⑤:4 (Figure 4(c)), shows a mixed fabric with two different raw materials: one part is a light brown fabric (similar to *Group 4*), the other part is a reddish-brown clay-rich fabric.

*Group 4* contains all the other samples[7], and could be separated into many sub-groups (Figure 4(d), (e)). Every sub-group has a well sorted calcareous and micaceous fabric.

For comparison, two pottery sherds were analysed. Though the ceramic workshop is adjacent to the mould making workshop, they used a very different raw material. Two pottery sherds belong to different fabrics but shared similar inclusions. Both sherds were made of a very fine clay-rich material mixed with mudrocks and calcite marbles. Inclusions in a large grain size are more frequently seen in ceramics. As for moulds and cores, only one shale in sample H31②:9 is of similar size.

As shown in Figure 4(h), some soils found at the site shared similar fabric as the moulds and cores. The left half of split image (h) is raw soil: it is similar to the unused core (Figure 4(d)). The right side of image (h) is burnt soil that could be found at the bottom of H73 and H79. It is certain that these burnt soils were not levigated, yet they exhibited a well sorted fabric.

*3.2.2. Summary*

There are several important discoveries through petrographic analysis.

Firstly, not every sample fits our common understanding about levigating the raw materials. Sample $H_{13}$③:1, H2①:126, H2②:81, H2⑤:4 have more matrix than others, which fits with the clay-silt ratio in some layers of the soil. On the other hand, clay pellets were also found in some of the samples (H2①:126, $H_{30}$②:295, H2⑤:9 and Ⅱ断面1③:18 etc.). These inclusions are clearly distinct from grog (Whitbread 1986). Some pellets are parallel to the mould surface, possibly the sign of not levigating the raw material. Otherwise, they would have been removed during the process.

Secondly, there is a difference in porosity through these samples. Despite those having air swirled in during the mould-making process, there are also some smaller pores (0.1-0.5mm). $H_{13}$③:1 only has large pores. Some scholars assumed that when raw materials are piled up and stored for a while, the porosity is lowered. Though this assumption still needs more experiments to confirm, it is clear there were differences between samples that used similar raw material.

Thirdly, grog tempering is not normally used. Only two samples from *Group 4* have inclusions that might be grog, this will be examined in a subsequent study.

Lastly, snail shell fragments varied between samples, some have abundant (H2①:126 and H2⑤:9) while others have none. This might suggest a different selection of raw material.

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[7] Except $H_3$①:5, Y1筛出采集遗物 and T040035DJ. These three are very different from the others. $H_3$①:5 is possibly red clay soil;

Y1筛出采集遗物 is from a midden of silts, excavators call it tempers pilling; T040035DJ is a clay block with finger prints.

### 3.3. SEM and X-CT results
### 3.3.1. Microstructure

Unlike ceramic, it is always hard to identify the category of casting-related remains: whether it is a model, a mould, or a core. They could even be confused with other clay productions and ceramics. Combining SEM-BSE imaging and compositional analysis, the category of samples may be verified.

Moulds and cores could be divided into two types: one is used and the other is not. The main difference between these two is the microstructure of the clay. For the used ones, the clay component on the surface is vitrified (Figure 5).

On the other hand, evenly applied "coating" was observed on some of the samples. e.g. $H_2$①:141. As shown in Figure 5, the microstructure of these layers is not vitrified, while those parts under these layers are vitrified. This suggests that the clay layer on this sample is not coating; it is likely contamination from burial soil. This discovery raised a question towards research on coatings, many studies only used surface analysis. Those results should be re-examined by SEM-BSE imaging before any further discussion.
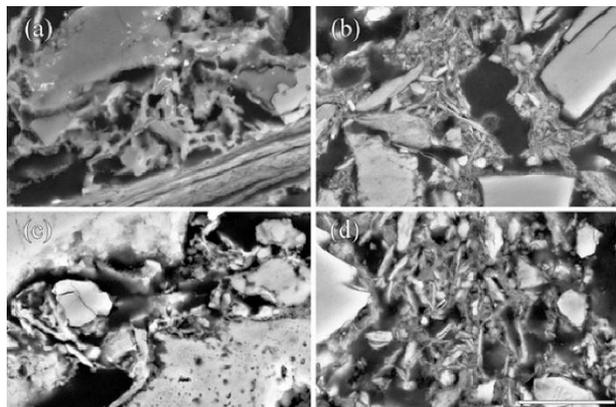


*Figure 5. SEM-BSE images (a) Surface of $H_2$①:103, clay vitrified; (b) Surface of $H_2$①:126; (c) $H_2$①:141, vitrified surface; (d) $H_2$①:141, clay contamination. (Scale = 10μm).*

Among the 20 technical ceramics for casting, seven of them have a different surface with vitrified clay, including $H_2$①:53, $H_2$①:103, $H_2$①:116, $H_2$①:141, $H_2$②:79, $H_2$⑤:4, and $H_{31}$②:9.

Combining with petrographic analysis, it can be concluded that $H_2$①:103 used a coating and $H_2$⑤:4 is layered. $H_2$①:55, $H_2$②:81, $H_2$③:7, $H_2$⑤:9, and Ⅱ 断面1③:18 also have a different surface, but only differ in colour and have no vitrified clay. It is possible that the coating of these five samples has gone missing, or they have never been put in use.

The clay-silt ratios of these technical ceramics were calculated. Most of them were lower than 1:2, which is very different from raw soil. Four samples have the higher clay ratio, with matrix around 1:1-1.2:1, including: $H_{13}$③:1, $H_2$①:126, $H_2$②:81, $H_2$⑤:4. These four samples have a similar clay-silt ratio as soils, it is possible that they were made with raw soil directly.

### 3.3.2. Chemistry

Principal component analysis (PCA) of EDX data (Table 1) reveals that two groups of samples are relatively similar (Figure 6):
1. $H_2$①:55, $H_2$③:7, $H_{13}$②:3, $H_{30}$②:295, $H_{31}$②:9, Ⅱ 断面1③:18 and $H_2$③:5, $H_3$②:17, $H_3$②:18
2. $H_2$①:103, $H_2$①:116, $H_2$①:126, $H_2$②:79, $H_2$⑤:9.
In the first group, six of them are technical ceramics and the other three are processed soils. This grouping is very similar to the petrographic groups.
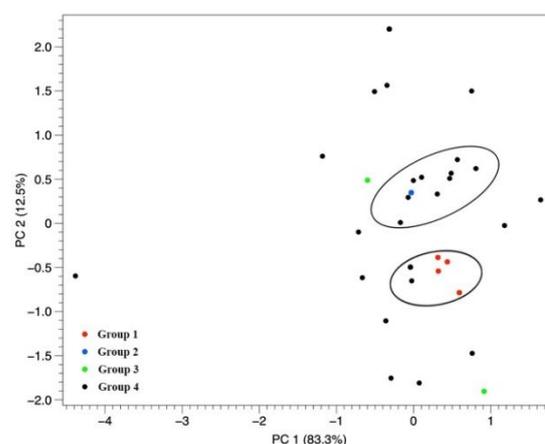


*Figure 6. PCA of mould, cores, and processed soils. PCA groups showed in circles while petrographic groups showed in colours.*

In the second group, all the samples are cores. Samples $H_2$①:103, $H_2$①:116, and $H_2$②:79 are in the same fabric group. It is possible that they were made from the same raw material. Samples $H_2$①:126 and $H_2$⑤:9 share a similar chemical composition as the other three, but were assigned to a different fabric group, probably as a result of casting and burning.

Combining the petrographic and SEM-BSE results, we observe no significant differences between the used ones and the discarded ones. Some of these samples shared a similar fabric (raw material). Therefore, the reason why some moulds and cores were never used is still unclear.

On the other hand, $H_2$①:116 and $H_2$②:79 are used cores and $H_2$①:103 is a tool mould: all three were used. Since $H_2$①:103 is coated and required a fine finish, it is questionable why craftsmen made them with the same material.

## 3.3.3. X-CT

Most samples from Yaoheyuan are single layered, but there is one special sample: H₂①:103. This is the mould for the handle part of a knife; the handle is decorated with liner pattern (Figure 7, bottom right).

A thin boundary is visible on CT image (as shown in Figure 7, the enlarged inset), dividing the mould into two parts. To achieve this effect, the part visible in the "square" must have been mixed with other raw materials after it had been dried. The continuous and uninterrupted parallel grooved pattern of the mould suggests that the engraving would be done after the mixing.
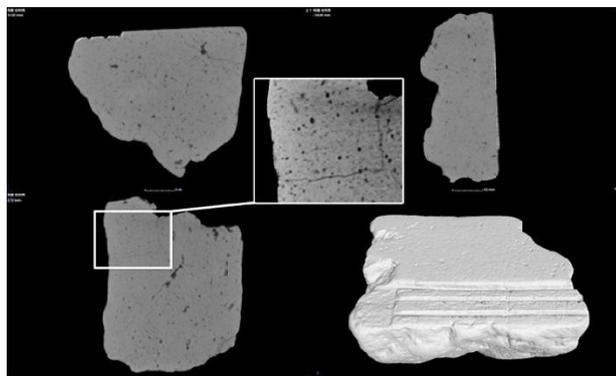


*Figure 7. X-CT result of H₂①:103, three sectional views showing metal residues and evidence of mixing materials of different dryness.*

This phenomenon indicates that raw materials at different degree of drying and hardening could be mixed, and the usable range of dryness for mould making can be broader than previously thought.

## 4. Discussion

Due to the limited number of samples available for this study, there are more questions than answers.

A large amount of Western Zhou bronzes has been found through excavations. But still, scholars could not reach an agreement on the production sequence. For these Western Zhou casting sites, some of them focused on casting ritual vessels, while others focused on tools and weapons. Some scholars argue that this is the result of the Zhou kingdom powering over the regional states.

It is obvious that the sites found up to date are not enough for the enormous bronze production of early Western Zhou period, Yaoheyuan is not exceptional.

Based on the samples found until now, Yaoheyuan's bronze casting activity may have focused on tools, weapons and horse fittings, with a small number of ritual vessels.

### 4.1. Raw material and treatments

Yaoheyuan is located in the western part of China, which presents an abundant aeolian loess source. But we still do not know what layers of soil were used and how they were used. This study reveals that craftsmen in Yaoheyuan may have not used a uniform technique.

Firstly, employing untreated or minimally treated soil is both sensible and highly effective. This assumption is supported by several indicators, including clay inclusions, high matrix ratio, shell fragments and a wide particle size distribution. This observation is not exclusive to Yaoheyuan, it exhibits both temporal persistence and widespread occurrence. For earlier periods, Miaopubeidi 苗圃北地 (Liu *et al.*, 2021), Taijiasi 台家寺 (Sun *et al.*, 2023), and Guoyuanzui 郭园咀[8] showed similar evidence. For later periods, several samples from Xincun 辛村[9] and lower Yangtze River area[10] might have been made also using the same technique. The raw materials coming from these sites are different, but they all match the structure of the local unprocessed soil. This is a newly found technique and requires more research. This suggests that rather than following the same tradition, perhaps craftsmen's personal choices resulted in varied bronze casting activities.

As for the silt inclusions (mainly calcite, also some shale and gravel), most of them have rounded to sub-rounded shape, suggesting that they were probably river sourced. An "inclusion piling" is found at the site near the canal. The minerals are not a straight match with the inclusions in the samples, it is more like they used left over/discarded material. From this, we may assume that craftsmen could select calcite from the silts available from the river. The river nearby could be the resource, but this still needs to be investigated.

Snail shell was likely naturally present in the raw materials. According to soil analyses, snail shell is a common inclusion in soils, only the type and amount vary on the basis of the different depths. According to the petrographic analysis, snail shells are not very commonly seen in the samples. For example, there are many in core sample H₂①:126 and none in core sample H₂③:7. This might indicate that a different soil processing procedure (snail shell fragments are

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[8] Jointly discovered by Yiyan Dong and Shirui Lin, in process.
[9] Have signs of bronze casting activities both from Western and Eastern Zhou period (1046B.C.-256B.C.), site is disturbed. Nine

casting-related remains were discussed by author in another article, in press.
[10] Mention by Ji Zhang with some cores from *Wu & Yue Culture* 吴越文化, un-published.

easy to wash away). On the other hand, not every snail shell found in the samples is a fossil. Therefore, it is likely that some of the craftsmen are using soil from not very deep depth in the ground.

*4.2. Making the moulds and cores*
When the raw materials are ready, the craftsmen would decide how to use them. This research finds that the technique is quite complex: craftsmen developed a few different techniques rather than using one constantly.

Firstly, the mixing of different types of soil occurred only for cores and moulds for weapons. These parts require relatively lower processing of the raw material and are made more randomly than others.

Secondly, there is a difference in the quantity of snail shell fragments, which might lead to a different material preference. But both samples cores and moulds contain shell fragments: this still requires more examination to understand.

Thirdly, core boxes or moulds for models could have been used in Yaoheyuan. Similar features were found in Xiaomintun 孝民屯, Anyang (The Institute of Archaeology, CASS, 2020), on some cores and moulds (e.g. 1600/ST2007_4:5, 1601/ST3107_3:26, 332-1/SH683:78, and 332-1/SH683:79). Rather than for "Pattern-block", insufficient attention has been paid to the technical aspects of this topic. It would be important to study more samples by micro-CT to investigate their inner structure.

*4.3. Surface treatments*
Previous studies have identified a thin layer applied to the moulds to achieve a smooth finish on the bronzes. Craftsmen in Yaoheyuan followed this tradition.

To date, all cores are not coated, the only layered one is H$_{13}$③:1 and the surface layer is not clay-rich. As for moulds, both layering and coating were observed. Despite those that cannot be defined by the type, others are: one horse ware (H$_2$①:55) and one arrow mould (H$_2$⑤:4) are layered; one knife mould (H$_2$①:103) is coated. With the burnt surface and no trace of vitrified clay, it is possible that the coating of most moulds has fallen off. Considering the soil mixing activity discussed in 4.1., some craftsmen might have chosen a different mould making procedure. They apply a thin calcareous layer over poorly mixed back layers, enabling the successful casting of smaller bronze objects. This method not only conserved the levigated raw materials, but also improved their efficiency.

*4.4. Origin of Yaoheyuan's casting technique*
Unfortunately, most tombs in Yaoheyuan were disturbed and only a few bronzes were found. Among them, only a ring-headed knife matches with one of the moulds. As a result, it is very difficult to draw some conclusions, and will need adjustments when more evidence is discovered.

As discussed before, several pieces of evidence might link Yaoheyuan with Anyang. But still, the link is not very strong. Kwang-chih Chang (Zhang G) stressed that when a state moves its capital, the metal workshop moves with it (Zhang 2013). When craftsmen move from one place to another, they usually spread the technique. Isotopic analysis could address this issue. As for Yaoheyuan, some strontium (Sr) isotopic results on tooth have shown that several people from Yaoheyuan were "immigrant".[11] It is possible that some craftsmen brought the casting technique from the Central Plain and adopted it with Yaoheyuan's local resources. To confirm this hypothesis, further isotopic analysis of oxygen (O) and carbon (C) is required.[12]

*4.5. Other questions*
There are a few more questions that still require further excavation to answer.

First question lies on the scale and type of casting activities. Until 2023, excavators only found a large number of slags from late Western Zhou period. This only confirms that Yaoheyuan exhibits casting and smelting activities, but the production scale still remains unknown.

Furthermore, it is also uncertain what types of bronzes were cast at Yaoheyuan. We do find some moulds and cores for ritual bronzes at the site, but the amount is relatively low. The study showed that none of them, including the only one bell core found in 2022 in H79, were used.

On the other hand, there is also evidence of trading. A *ding* leg (2017PYIM7:158, unpublished) found in grave M7 has a core with grass tempering. Since excavators had not found any cores with grass temper before, this *ding* is highly possible to have been imported from other States. If Yaoheyuan had a large production scale on ritual bronzes, why did they import?

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[11] Research done by Chunyan Zhao, unpublished.
[12] Zihua Tang has done some research by using the δ$^{18}$O open database, he stressed that the δ$^{18}$O have a specific distribution on geographical scale of China, which could be helpful on the identification where's the people's origin.

## 5. Conclusion

At the Yaoheyuan site bronzes were cast; it is possible that their technique comes from the Central Plain of China (Anyang probably). The authority of the Zhou dynasty might have been demonstrated through its control over the types of bronzes they could make.

Craftsmen might have adjusted the mould-making technology with the soil sources, selecting specific layers of the soil to be used directly. Nevertheless, there are more questions than answers about this site. Excavations continue on the remaining three quarters of unexcavated area, and we could expect new findings soon.

Table 1. Sample list and chemical compositions (EDX analyses, normalised wt.%)

| No. | 编号 | Category | Fabric group | $Na_2O$ | MgO | $Al_2O_3$ | $SiO_2$ | $K_2O$ | CaO | MnO | $TiO_2$ | FeO | $P_2O_5$ | $SO_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | H₂①:53 | Crucible | 4 | 2.0 | 2.4 | 12.9 | 66.3 | 2.7 | 8.2 | 0.0 | 0.6 | 4.7 | 0.1 | 0.1 |
| 2 | H₂①:55 | mould | 4 | 2.2 | 2.5 | 12.3 | 66.0 | 2.4 | 10.5 | 0.0 | 0.2 | 3.7 | 0.1 | 0.1 |
|   |   |   |   | 2.1 | 2.4 | 11.9 | 66.2 | 2.6 | 10.5 | 0.0 | 0.5 | 3.4 | 0.1 | 0.2 |
| 3 | H₂①:103 | mould | 1 | 2.1 | 2.5 | 12.2 | 65.2 | 2.9 | 9.6 | 0.1 | 0.5 | 4.2 | 0.2 | 0.1 |
| 4 | H₂①:116 | Core | 1 | 2.6 | 2.3 | 12.8 | 65.9 | 2.3 | 9.0 | 0.2 | 0.5 | 3.8 | 0.5 | 0.1 |
|   |   |   |   | 2.1 | 2.2 | 12.7 | 65.7 | 2.5 | 9.6 | 0.0 | 0.5 | 4.4 | 0.1 | 0.1 |
| 5 | H₂①:126 | Core | 4 | 2.0 | 2.7 | 13.0 | 64.4 | 2.5 | 10.1 | 0.0 | 0.6 | 4.3 | 0.3 | 0.2 |
| 6 | H₂①:134 | Core? | 4 | 2.1 | 2.8 | 12.9 | 64.2 | 3.9 | 8.6 | 0.0 | 0.6 | 4.7 | 0.1 | 0.1 |
| 7 | H₂①:141 | Mould | 4 | 1.9 | 3.9 | 14.6 | 52.8 | 2.2 | 14.7 | 0.1 | 0.6 | 6.8 | 1.9 | 0.1 |
| 8 | H₂②:42 | Tuyere nozzle | 4 | 2.2 | 2.4 | 10.8 | 66.8 | 2.4 | 10.8 | 0.2 | 0.7 | 3.6 | 0.1 | 0.0 |
|   |   |   |   | 2.0 | 2.6 | 11.1 | 69.0 | 2.0 | 8.6 | 0.2 | 0.6 | 3.9 | 0.1 | 0.0 |
| 9 | H₂②:79 | Core | 1 | 2.2 | 2.2 | 12.4 | 65.2 | 2.3 | 9.4 | 0.0 | 0.6 | 4.5 | 0.2 | 0.0 |
|   |   |   |   | 1.7 | 1.8 | 11.9 | 67.7 | 2.9 | 9.1 | 0.2 | 0.6 | 3.9 | 0.0 | 0.0 |
| 10 | H₂②:81 | Core | 4 | 2.5 | 2.8 | 13.3 | 62.7 | 2.6 | 10.7 | 0.0 | 0.6 | 4.8 | 0.1 | 0.0 |
| 11 | H₂②:105 | Core | 4 | 1.8 | 2.5 | 11.6 | 64.1 | 2.5 | 12.3 | 0.0 | 0.6 | 4.6 | 0.0 | 0.1 |
| 12 | H₂②:142 | Mould? | 4 | 2.1 | 2.4 | 11.5 | 64.3 | 2.2 | 12.9 | 0.0 | 0.4 | 3.9 | 0.2 | 0.1 |
| 13 | H₂③:5 | Processed soil | 4 | 2.1 | 2.5 | 12.2 | 65.0 | 2.2 | 10.8 | 0.1 | 0.5 | 4.2 | 0.2 | 0.1 |
| 14 | H₂③:7 | Mould? | 4 | 2.4 | 2.6 | 11.7 | 66.8 | 2.0 | 10.0 | 0.2 | 0.5 | 3.5 | 0.2 | 0.0 |
| 15 | H₂⑤:9 | Core | 4 | 2.2 | 2.5 | 12.7 | 64.3 | 2.7 | 9.8 | 0.3 | 0.7 | 4.6 | 0.1 | 0.1 |
| 16 | H₂⑤:4 | Arrow mould | 3 | 2.5 | 2.8 | 12.4 | 63.1 | 2.1 | 11.5 | 0.2 | 0.4 | 4.7 | 0.2 | 0.2 |
|   |   |   |   | 2.5 | 3.2 | 13.6 | 66.5 | 2.3 | 7.7 | 0.0 | 0.6 | 3.2 | 0.3 | 0.0 |
| 17 | H₃①:5 | Processed soil | ? | | | | | | | | | | | |
| 18 | H₃②:16 | Furnace wall | — | | | | | | | | | | | |
| 19 | H₃②:17 | Processed soil | ? | 2.2 | 2.4 | 11.9 | 66.0 | 2.4 | 10.4 | 0.1 | 0.5 | 4.0 | 0.0 | 0.1 |
| 20 | H₃②:18 | Processed soil | ? | 2.4 | 2.7 | 12.1 | 65.4 | 2.1 | 10.3 | 0.2 | 0.5 | 3.7 | 0.6 | 0.1 |
| 21 | H₁₃② | Processed soil | ? | 1.8 | 2.6 | 13.6 | 63.4 | 3.2 | 9.2 | 0.2 | 0.8 | 5.0 | 0.2 | 0.1 |
| 22 | H₁₃②:3 | Core | 4 | 2.1 | 2.8 | 12.5 | 64.1 | 2.4 | 10.6 | 0.2 | 0.5 | 4.4 | 0.1 | 0.2 |
| 23 | H₁₃③:1 | Core | 4 | 1.9 | 2.4 | 12.1 | 63.7 | 2.2 | 12.5 | 0.2 | 0.4 | 4.4 | 0.3 | 0.0 |
| 24 | H₃₀②:295 | Core | 4 | 2.1 | 2.5 | 12.4 | 64.5 | 2.3 | 10.8 | 0.0 | 0.6 | 4.4 | 0.3 | 0.1 |
| 25 | H₃₁②:4 | Furnace wall | — | | | | | | | | | | | |

Table 1 (continued)

| No. | 编号 | Category | Group | Na$_2$O | MgO | Al$_2$O$_3$ | SiO$_2$ | K$_2$O | CaO | MnO | TiO$_2$ | FeO | P$_2$O$_5$ | SO$_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | H$_{31}$②:9 | Core | 2 | 2.2 | 2.7 | 12.4 | 64.6 | 2.2 | 10.8 | 0.1 | 0.4 | 4.2 | 0.2 | 0.2 |
| 27 | Y$_1$②:11 | Furnace wall | 4 | 2.3 | 2.5 | 12.7 | 61.6 | 2.9 | 12.6 | 0.0 | 0.8 | 4.6 | 0.0 | 0.1 |
| | | | | 2.3 | 2.7 | 12.6 | 62.6 | 2.8 | 11.1 | 0.0 | 0.7 | 4.9 | 0.1 | 0.1 |
| 28 | Y$_1$②:12 | Furnace wall | 4 | 2.3 | 3.0 | 13.2 | 63.3 | 2.8 | 9.8 | 0.0 | 0.7 | 4.5 | 0.3 | 0.1 |
| 29 | Y$_1$②:13 | Furnace wall | 4 | | | | | | | | | | | |
| 30 | Y$_1$筛出采集遗物 | Processed soil | — | | | | | | | | | | | |
| 31-1 | II$_{断面1}$③:18 | Core | 4 | | | | | | | | | | | |
| 31-2 | II$_{断面1}$③:18 | Core | 4 | 2.0 | 2.7 | 12.5 | 64.8 | 2.2 | 11.0 | 0.0 | 0.5 | 4.2 | 0.2 | 0.1 |
| 32 | T040035DJ | Processed soil | — | 0.2 | 2.0 | 4.9 | 13.8 | 0.6 | 75.5 | 0.3 | 0.3 | 1.4 | 0.5 | 0.4 |
| 33 | 2018PYIY①① | Pottery | — | | | | | | | | | | | |
| 34 | T040037② | Pottery | — | 2.3 | 2.8 | 15.9 | 57.7 | 3.2 | 11.2 | 0.1 | 0.7 | 5.7 | 0.2 | 0.2 |
| | | | | 2.0 | 3.0 | 16.2 | 56.3 | 2.4 | 13.4 | 0.1 | 0.5 | 5.6 | 0.2 | 0.2 |

## Credit authorship contribution statement

All authors contributed equally.

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