Rediscovering the largest kiln site in the middle Yangtze River Valley: insights into Qingbai and grey-greenish ware production at Husi kiln site based on bulk chemical analysis

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Abstract

This paper presents new data from the Husi kiln site, Hubei Province, China, where the unusual size calls into question the primacy of Jingdezhen in porcelain production in medieval China. With its over 180 kilns, the site rivals Jingdezhen in size, yet it has found no mention in textual accounts. The wares produced at Husi include Qingbai and grey-greenish ware of the Tang and the Song periods (seventh to thirteenth century AD). This paper presents compositional data obtained using LA-ICP-MS on samples from five kilns at Husi, comparing them with published data from other kilns. The data set Husi apart, thus allowing for fingerprinting its wares. Based on bulk chemical analysis, the paper furthermore explores the idea that Husi combined elements of southern and northern technologies, thus connecting these two ceramic traditions that previously had been seen as being entirely separate. Some key elements of the early Qingbai ware glaze from Husi resemble wares from Jingdezhen, suggesting a connection between the two sites; however, the glaze recipes for later wares found at Husi differ, indicating that its customer base and marketing strategy changed over time. Furthermore, the iron content of the grey-greenish ware from Husi is extraordinarily high, indicating a unique glaze recipe and production technology independent from Jingdezhen.

Keywords Qingbai ware · Grey-greenish ware · Ceramic technology · Chemical composition · Husi kiln site · Jingdezhen

Introduction

In the history of Chinese high-fired wares, broadly speaking the South is best known for greenwares and the North for whitewares. Southern and Northern potters produced specific wares using different glaze recipes and technological approaches (Ma et al. 2018). The glaze of northern white-ware was mainly made from limestone while in the south botanic ash was the main material for manufacturing the greenwares that the regions is mostly known for (Wu et al. 2020). It has long been unclear if the two production traditions were ever connected, partially because no large kiln sites had been found in the area in between. The discovery of the Husi kiln site in 1979 changed this, but due to the lack of archaeological fieldwork, the site and its products still remains poorly understood. Many questions remain

unanswered, including the date of the site, the range of its products, the technological and organizational details of production, the customer base, and the reasons for its decline. To explore these questions further, the present paper first presents new compositional data for ceramic samples taken from recent survey and excavation work at Husi and then makes a comparison with data from similar wares from other contemporary major ceramic production centres. Besides providing a first glimpse into the nature of ceramic production at Husi, this new data also provide a foundation for future research into the connection between ceramic production in Southern and Northern China.

Background

The Husi kiln complex was discovered in 1979 by the Wuhan City Institute of Archaeology and Wuhan City Museum. What surprised the archaeologists was that there is no mention of this kiln site in historical accounts (Liu et al. 2016). The spatial extend of the Husi kiln site is 40 by 30 km (about 500,000 m²), stretching over eight modern-day towns and 50

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Fig. 1 Geographic location of the Husi kiln complex and the distribution of the 180 kilns recorded during recent survey work. This study collected ceramic sherds from five kilns which have been marked on the map. The location data of kilns can be found in Appendix A

villages (Qi 2007). At the time of the initial discovery, Husi was reported as encompassing 180 kilns of various sizes, the smallest around 6 m, the largest over 50 m long, their structure making them southern-style dragon kilns (Chen et al. 1993). Recent survey work has shown that there may be many more kilns than previously assumed, maybe as many as 300 (Qi 2007). They are grouped around two lakes, Futou Lake and Liangzi Lake, which are connected to the Yangtze River via various channels (Fig. 1; Appendix A). The kiln complex was thus connected to major routes of transport.

The convenient geographic location and the large number of kilns at the site make Husi an important discovery for research on ceramic production and dissemination in Hubei Province and beyond. Nevertheless, there were some issues with getting the site officially recognized (Xiong 2019), and in the over 30 years since its discovery, it saw only two instances of fieldwork, neither of them fully reported, making it impossible to compare the Husi kiln products with Qingbai ware from other kilns. Laboratory analysis has likewise been lacking (Liu 2019). Since 2018, advances have been made on both counts, with archaeologists (including the lead author) conducting extensive surveys and starting systematic sampling and analytical work on material from the site.

These recent surveys have shown that the main product of the Husi kiln complex was Qingbai 青白 (blue/green¹-white) ware, a type of porcelain made under the Song Dynasty (960–1279 AD) and the Yuan Dynasty (1271–1368 AD). It has a bluish tint and is also referred to as Yingqing 影青 (shadow blue/green) ware (Pierson 2002:6–7). Based on archaeological fieldwork, 126 of the 180 kilns originally reported from the Husi kiln complex have been shown to have produced Qingbai ware (Liu 2006; He et al. 2000; Wuhanshi et al. 1998). This demonstration of the considerable extend of Qingbai production raises the question of connections with other Qingbai-producing kiln complexes. Jingdezhen has long been known as the largest kiln site producing high-quality Qingbai wares at large scales, and so it has been generally assumed that the Qingbai ware production techniques were developed there (Chen et al. 1993 and 2007; Zhang et al. 2018). It has been suggested that the Jingdezhen kiln potters then spread these techniques to other

¹ The character *qing* 青 refers to a colour somewhere between blue and green. The term has no precise equivalent in English and is usually translated either as blue or green or blue-green. In the following, we will be using the term Qingbai ware to avoid confusion.

ceramic production centres such as Fanchang kiln in Anhui, Dehua kiln in Fujian, and Nanfeng kiln in Jiangxi. Many studies have found both typological and chemical evidence that Qingbai wares from Jingdezhen were transported to several Qingbai ware production centres, including sites in Guangxi, Guangdong, Fujian, and Hunan Provinces, and this is also seen as evidence that Jingdezhen potters may have travelled to these places along with their wares to spread Qingbai ware production techniques (Liu and Bai 1982; Wang et al. 2020; Zhu et al. 2012).

The discovery of the Husi kiln complex challenges the traditional view of a single source of Qingbai ware. This development supports the recent findings of a small number of researchers who, on the basis of material from other sites, suggest that Qingbai ware might have been created not solely at Jingdezhen but at several sites (Cui and Zhu, 2018; Cui and Zhu, 2016; Yang and Zhang 2006; Yang et al. 2010). Additionally, the enormous size of the Husi kiln complex and the wide range of ceramics found there suggests large-scale production of various ceramic types, potentially rivaling production at Jingdezhen in certain wares. Furthermore, the convenient location of the Husi kilns along the shores of two lakes connected with major water transport systems would have placed it in a position to ship goods far and wide, while Jingdezhen was in a geographically slightly less advantageous location. Nevertheless, it is Jingdezhen that has become world-famous, while Husi has lain forgotten for many centuries. This paper aims to revise this view by providing the first insights into ceramic production at Husi and furnishing the first set of compositional data for comparison with materials from other contemporary kiln sites.

Elements of northern ceramic technology at Husi

Most of the kilns discovered in the Husi kiln complex are dragon kilns, a design which typical of southern ceramic production. Additionally, a small domed firing chamber with a horseshoe-shaped plan was found in the Qingshan kiln area, from which some white wares that strongly resemble northern products were excavated (Luo and Tu 2001; Yang 2000). He et al. (2000) suggest that the structure may have been part of a dragon kiln, but this is by no means certain since the feature was too badly damaged to determine the overall shape of the kiln (He et al. 2000; Qi 2007; Tian et al. 1991; Tian, 1990). Tian et al. (1991) report that there were several other small dome-shaped structures that had been badly damaged by modern construction projects, and they likewise suggest that these may have been the firing chambers of dragon kilns, but offer no conclusive evidence. Until this issue is resolved, there remains a tentative possibility that some of the severely disturbed features at Husi could have had northern characteristics, though equally these could

also have simply been small domed biscuit-firing structures or even small lime kilns.

In addition, excavation reports from various kilns at Husi report the discovery of the use of kiln-spurs, i.e. kiln furniture common in the North (He et al. 2000; Luo and Tu 2001; Peng et al. 1993; Qi, 2004, 2007; Tian et al. 1991; Xiong, 2019; Yang, 2000). Some of the excavated products also show traces of the use of spur firing technology (Fig. 2a). The earliest use of kiln spur firing technology in China (Fig. 2b) has been reported from Yaozhou and Huangbao kilns which were important northern kilns during the Five Dynasties (907–979 AD) and Song Dynasty (Ding, 2016; Liu, 1999). In China, kiln-spur firing technology has been used at only a few kiln sites, most of which are major northern kilns such as the Ru, Jun, and Ding kilns (Liu, 2004). Qin (2008) believes that these northern kiln sites were influenced by the Yaozhou and Huangbao kilns. Based on previous excavation reports, Xiong (2019) notes that at Husi kiln-spur, firing technology was used in producing grey-greenish ware during the Five Dynasties period, most likely due to influence from the Yaozhou and Huangbao kilns. The discovery of kiln-spurs thus seems to indicate that ceramic production at Husi was influenced by northern kiln sites and from a very early date.

Furthermore, Xiasi kiln at Husi yielded celadon products that have a thicker glaze similar to that common to products from Yaozhou kiln. A typological comparison of wares from the two sites (Fig. 2c and d) shows that glaze colour and the thickness of the clay body of the Xiasi celadon are similar to that of products from Yaozhou kiln. These similarities combined with the presence of the kiln-spurs suggests that elements of the ceramic technology practised at Yaozhou kiln may have spread to the Husi kilns during the Five Dynasties period.

Combining typological research and scientific analysis

Based on typological comparison with reliably dated objects, previous studies have suggested that the Husi kiln site might have been in operation from the Five Dynasties period until the Ming Dynasty (1368–1644 AD) (He et al. 2000; Peng et al. 1993; Wuhanshi et al. 1998). When comparing the shape and colour of the Husi Qingbai ware with funerary ceramics from grave sites in Hubei dating to the Northern Song Dynasty (960–1127 AD), Liu Hui (2019) observed significant similarities suggesting that the objects found in these graves may have been produced at Husi rather than the Jingdezhen Hutian kiln as had been previously assumed (Chen et al. 1995). Based on later typological work, Chen Bingbai reconsidered his views and now argues that the Qingbai ware found in local graves was produced at Husi

Fig. 2 (a) Traces of the use of spur firing technology on a ceramic sherd from Hushi; **b** schematic diagram of the use of kiln spurs for firing ceramics; **c** Yaozhou celadon product from the Palace Museum; **d** Hushi celadon from Xiasi kiln.

rather than Jingdezhen Hutian (Chen Bingbai, personal communication).

The founding date of the Hushi kiln site has also been actively discussed. Tian Haifeng (1990) suggested that the Hushi production commenced in the late Eastern Han Dynasty (25–220 AD) based on the *Hou Hanshu*,² which reports that the King of Wu, Sun Quan (reigned 229–252), moved his capital to E'zhou (modern-day Wuhan City) and began to have ceramic products for daily use made locally.³ As the earliest layers at Hushi contained coins from the Five Dynasties period, Peng et al. (1993) argued that Hushi kiln might have been founded at that time. Based on typological comparison between the grey-greenish wares found in the earliest layers of Hushi with securely dated ceramics from the Northern Song, Yang and Chen (2005) suggested

that ceramic production at the site commenced during that period. However, Chen (2010) has called into question all of these dates, saying instead that typological comparison was an outdated approach for establishing the absolute date of an artefact. Indeed, the period of production of a certain type may differ between regions, continuing in one area, while it has long fallen out of popularity in another. Furthermore, objects found in graves may have circulated above ground for decades or even centuries before finding their last resting place. Additionally, in the case of Chinese porcelain, many objects have been in collections for many centuries and have not been scientifically excavated; they thus lack the secure archaeological context that can help with dating the items in question. Relying exclusively on a typological approach to establish the date of the Hushi kilns and its products is therefore indeed problematic. Furthermore, ceramics of similar outward appearance sharing the same shape, decoration, and/or colour may have been produced using different raw materials or techniques (Roux 2019), so it is advisable to combine typological and technological analysis in any assessment of production data and/or locale.

Nevertheless, although there might be some subjectivity involved, typological analysis can provide a basis for establishing the approximate relative chronological position of different Qingbai wares. The present study suggests that combining typological comparison with chemical analysis

² The *Hou Hanshu* 後漢書, the History of the Later Han, was compiled by Fan Ye in the fifth century AD and covers the time of the Eastern Han Dynasty (25–225 AD). It is one of the official Twenty-Four Histories.

³ The *Hou Hanshu* records that “He moved the capital to E'zhou, renaming it to Wuchang City, and ordered craftsmen to make ceramics there for the daily use of common people, dividing the craft industry for the benefit of the people” (Quan qiandu E'zhou, hao Wuchang, minggong jiang jiudi zhici yi zhimin yong, fen jianye zhi min qiajia yi yizhi 权迁都鄂州, 号武昌, 命工匠就地制瓷以致民用, 分建业之民千家以益之) (Fan 5th c. AD (1939): 15).

Fig. 3 Geographic location of the Husi kiln complex, Anhui Fanchang kiln, and Jingdezhen Hutian kiln. The location of the Hutian kiln and Fanchang kiln was extracted from Wang et al. (2020) and Yang Yuzhang et al. (2010), respectively

and stratigraphic and other contextual information obtained by archaeological fieldwork provides a more robust approach for assessing the date and development of Husi kiln complex. Previous studies have successfully used a comparative analysis of materials from Qingbai ware kilns with an established chronology (primarily Jingdezhen) to date other Qingbai ware kilns such as Xicun kiln in Guangxi Province and Mingqing kiln in Fujian Province (Wang et al. 2020; Wu et al. 2019; Zhu et al. 2012). Accordingly, the present study conducts chemical analysis to similarly characterize the Husi kiln products and compare them with wares found at other sites.

Comparing Husi and Jingdezhen production

Jingdezhen is arguably the most well-known porcelain production site in China. Based on archaeological evidence, it has been active since the sixth century AD, reaching fame from the Ming period at the latest when it was made the official imperial kiln (Vainker 2005:176–213). In terms of transportation networks, the location of Jingdezhen seems less ideal than Husi, which is directly connected with the Yangtze River, since Jingdezhen potters first had to transport their ceramics to the Yangtze River via the Jiujiang River. However, Jingdezhen was more than compensated for by abundant deposits of high-quality porcelain stone (*petunse*) and kaolinite and originally would have been surrounded by dense pine woods for fuel (Vainker 2005:176): resources essential for maintaining large scale production over a considerable time.

Interestingly, there is a strong similarity between Jingdezhen and Longquan, which also was established in a remote locale. Longquan also has abundant woodland for fuel and high-quality porcelain stone despite being located in a low-density population zone and connected to its export markets only by a relatively small river. It has been suggested that Longquan became the dominant celadon production centre because the preceding Yue kilns had used up all their woodland, a measure of how important fuel would have been for the development and survival of major kiln complexes (Nigel Wood, personal communication).

Probably most well-known imperial kilns at Jingdezhen are Zhushan and Hutian. Archaeological evidence shows Hutian to have been in use from the Five Dynasties to the mid-Ming period and Jingdezhen as a whole used to have about 300 kilns. In comparison, based on survey work at Husi, Qi, (2007) has estimated that Husi may once have held just as many kilns rather than only the 180 previously recorded.

The Husi kiln site is located in the middle reaches of the Yangtze River which has a slightly higher elevation than the Hutian kiln site itself (Fig. 3). There are less than 20 km between the Husi kilns and the Yangtze and the road goes slightly downhill, making shipping of large amounts of ceramic products fairly easy (Liu, 2006). In contrast, the Jingdezhen Hutian kiln is only indirectly connected to the Yangtze, meaning that its products had to be shipped via Jiujiang (Kerr and Wood 2004: 127–129).

If it is assumed that a similar southern-style porcelain stone (*petunse*) was being used, it seems that the vast scale

Fig. 4 Grey-greenish ceramic products from Husi kiln and Jingdezhen kiln: **a** Tang Dynasty sherd from the Jingdezhen Lantian kiln (photo from Wu et al. 2020); **b** sherd found at the Yangjiaxie kiln, Husi (photo taken by Li Zihan)

of production and convenient location should have enabled Husi kiln to challenge the dominant position of Jingdezhen Hutian kiln during the Song Dynasty. However, previous reports of archaeological investigations at Husi mentioned that the quality of the Qingbai ware from Husi was much lower than that of similar products from the Jingdezhen Hutian kilns (He et al. 2000; Liu, 2006; Wuhanishi et al. 1998; Tian et al. 1991).⁴ They therefore suggest that the target market for the Husi kiln production may have been the inhabitants of nearby cities and villages who purchased them as wares for daily use. Based on typological comparison, these same reports also argue that the Qingbai ware production technology used at Husi may have been adopted from potters at the Jingdezhen Hutian kiln. Other studies, however, observe that the Qingbai ware unearthed from the earliest layer of Wangma kiln (marked in Fig. 1) at the Husi kiln site is of much higher quality than those found in later layers, in some cases even of higher quality than items from the Jingdezhen Hutian kiln (Liu Zhiyun et al. 2016; Qi 2007). This calls into question the assumption that Husi kiln only produced low-quality Qingbai ware. Indeed, based on current evidence, the early Husi Qingbai ware might have challenged the dominant position of the Jingdezhen Qingbai ware at least for a time.

What makes this comparison more interesting, however, is the observation that the granitoid-based porcelain stone (*petunse*) that typifies Jingdezzhen and most southern Chinese production is in fact absent at Husi. Instead, the immediate area has rich clay deposits based on Jurassic feldspathic sandstone (Chen et al. 1993) where the corresponding relatively high levels of potassium oxide act as efficient flux,

allowing the production of high-quality wares with a very white body and a smooth surface. This type of raw material is still available locally (Zhong et al. 2020), so it cannot have been the lack of high-quality raw materials that made potters at Husi concentrate on higher-volume lower-quality ware in later periods. An alternative explanation could be the lack of imperial patronage that held Husi back in comparison to Jingdezhen, but further research on the exact timeline and changes in nature and organization of ceramic production at Husi is needed to address this question.

Another recent study has focused on early phase products at Jingdezhen Lantian kiln, near Hutian, which mainly produced grey-greenish ware during the Tang Dynasty (618–907 AD) (Wu et al. 2020). These early products greatly resemble the early grey-greenish ware from Husi (Fig. 4) that were previously considered to date to the Five Dynasties period. These new analyses thus contribute to the discussion on the date of the Husi kiln and its connections with Jingdezhen.

Fingerprinting the Husi products

To establish the chemical and technological characteristics of the Qingbai ware produced at Husi and make progress towards dating the kiln and its product, this paper makes a comparison with wares from Jingdezhen Hutian kiln as well as other Qingbai ware production centres: Fanchang kiln in Anhui Province and Dehua kiln in Fujian Province. This follows the methodology successfully used by other studies of various Qingbai ware production centres that have applied trace element analysis to determine provenance to explore the origin of Qingbai production techniques (Wang et al. 2020; Wu et al. 2019; Zhu et al. 2012). Excavations at Qingbai ware production centres such as Dehua kiln and Xicun kiln in Guangxi Province and Chaozhou kiln in Guangdong Province have uncovered Qingbai wares that have since been shown unequivocally, through their Nb–Ta and Zr–Hf ratio, to have been produced at Jingdezhen kiln (Gelman

⁴ Quality is generally assessed based on visual assessment, judging the clay body by its whiteness and the ware by its surface sheen and smoothness, criteria that are generally assumed to have been shared by producers as well as consumers in the past and are used by connoisseurs and collectors in the present to assess the value of ceramic pieces.

Table 1 Detailed information on samples from Husi analysed in this study

<i>Kiln</i>	<i>Number</i>	<i>Type</i>	<i>Date</i>	<i>Appearance</i>
Wangma kiln	Wm1-5, Wm7	Qingbai ware (earliest (1st) layer)	Song Dynasty	Paste: pure white; glaze: Icy bluish with cracks
	Wm8-Wm12	Qingbai ware (2nd layer)	Song Dynasty	Paste: pure white; glaze: white with green
	Wm13-16, Wm19	Qingbai ware (3rd layer)	Song Dynasty	Paste: white with grey shallow; glaze: yellow-whitish with bubbles
Fushan kiln	Fs1-Fs7, F10-14	Qingbai ware	Song Dynasty	Paste: pure white; glaze: white with green
Tuyuan kiln	Ty1-Ty5,	Qingbai ware	Song Dynasty	Paste: pure white; glaze: Icy-bluish with cracks
Xiasiwang kiln	Xs1-Xs4	Celadon	Unclear	Paste: shallow grey; glaze: green
Yangjiaxie kiln	YJ1-YJ3, YJ6,YJ8	Grey-greenish ware	Unclear	Paste: brown; glaze: brown with green

et al. 2014; Wang et al. 2020). This is seen by these authors as confirming the hypothesis that Qingbai ware production originated at Jingdezhen.

The present paper likewise uses Nb–Ta and Zr–Hf ratios to test for possible connections between Husi and Jingdezhen. The ratio of niobium (Nb) and tantalum (Ta) is fixed in the rock and subsequent weathering, and deposition of the resulting clays does not change the Nb–Ta ratio (Ding et al. 2013; Gelman et al. 2014; Wang et al. 2020), nor does levigating or elutriation the clay, or the firing process. Therefore, it is possible to differentiate outwardly similar Qingbai ware items produced in different regions based on their Nb–Ta ratios, even if their major elements are very similar. A second trace element ratio, that of Zr:Hf, works along similar principles and is frequently used to find the origin of export porcelain (Xu et al. 2019).

In combination, these two ratios can be used as a fingerprint to distinguish Qingbai ware made at Husi from Qingbai ware produced elsewhere, to provide more information about the relationship between Husi and other contemporary kiln sites, in particular Jingdezhen. The aim is to provide insights into the role the Husi kiln complex may have played during the Song Dynasty on the porcelain market.

Material and methods

LA-ICP-MS (laser ablation inductively coupled plasma mass spectrometry) analysis was used to assess the chemical composition including major, minor, and trace elements of both the glaze and clay body of Qingbai ware sherds from kilns at Husi which had undergone archaeological investigation, including Wangma kiln (16 samples), Fushan kiln (7 samples), Tuyuan kiln (5 samples), Yangjiaxie kiln (5 samples), and Xiasi kiln (4 samples) (Fig. 1; Table 1). Wangma is the only locale at Husi where a clear stratigraphy could be observed; therefore, 5–6 samples each were taken from three separate layers to explore the development of the Husi Qingbai ware products over time. Additionally, the composition of all samples from Husi was compared with similar

products from Jingdezhen and other major kiln sites, whose chemical composition has been previously published, to investigate whether they shared the same glaze formula and production technology.

Sample description

This ongoing study is supported by the Archaeological Institute of Wuhan City, which to date has provided 225 samples for visual analysis including grey-greenish ceramic sherds, Qingbai ceramic sherds, and celadon (Fig. 5). From these, 55 sherds with a well-preserved glaze layer were chosen for compositional analysis (Table 1).

There are 19 Qingbai ware specimens from Wangma kiln. Of these, Wm1–Wm7 were collected from the earliest (1st) layer, Wm8–Wm12 from the 2nd layer, and Wm13–Wm19 from the 3rd layer. Fushan kiln provided 11 Qingbai ware samples, Tuyuan kiln five high quality sherds, and there were five celadons from Xiasiwang kiln. In addition to these Qingbai ware samples, eight grey-greenish ware sherds were selected from Yangjiaxie kiln. The guiding criterion for selection was to choose samples where the contact between the glaze layer and the clay body could be clearly observed for conducting laser ablation. The celadon samples were too few in number for statistical significance, but nevertheless these were included to give a first impression of the range of wares that were produced at Husi. Future research aims to compare a larger number of celadon samples from Husi with samples from Longquan kiln and other celadon production centres. This first paper focuses on the (currently) more accessible grey-greenish and Qingbai wares.

Methods of analysis

The pre-treatment and LA-ICP-MS analysis of the Husi wares were performed at the CAS Key Laboratory of Crust–Mantle Materials and Environments, University of Science and Technology of China. The analysis was conducted using a Coherent ArF excimer UV 193 nm wavelength laser

Fig. 5 Husi Qingbai ware and grey-greenish ware samples unearthed from five kilns at the Husi kiln site: Wangma I (i.e. layer 1 at Wangma), Wangma II (i.e. layer 2 at Wangma), Tuyuan, Xiasi, Fushan, and Yangjiaxie (photos taken by Li Zihan)

ablation system (GeoLas pro) coupled with Agilent 7700e quadrupole ICP-MS.

The pre-treatment process involved cutting and polishing test specimens, resin embedding, as well as polishing resin targets. The samples were cut using a 0.8-mm-thick diamond wire cutter and polishing the cross-section of the specimens to preserve both the clear glaze layer and the clay body layer.

The glaze layers were observed using a polarizing light microscope to discriminate between body and glaze. The 38-micron spot size and a 10 Hz ablation frequency were used for single spot ablation. The chemical compositional

data were calculated using multiple external references without internal standards provided by ICP-MSDataCal, following an approach proposed by Liu Yongsheng and his team in 2008 (Liu et al. 2008). The reference materials used were NIST SRM 610 and NIST SRM 612 from the National Institute of Standards and Technology and the USGS (United States Geological Survey) reference glasses BCR-2G, BHVO-2G, and BIR-1G. NIST SRM 610 was used as a monitoring standard. BCR-2G, BHVO-2G, and BIR-1G were used as external calibration standards, and the NIST SRM 612 was used as a secondary standard (Hou

Fig. 6 $\text{Al}_2\text{O}_3/\text{SiO}_2$ - K_2O and Na_2O scatter plots for the clay body of Qingbai ware sample of Husi and Jingdezhen Hutian kiln. The major element data of Jingdezhen Hutian Qingbai ware ($N=15$) is from Wu et al. (2020)

et al. 2020). The accuracy and precision achieved by the analyses of the secondary standard NIST SRM 612 (including absolute error, relative error, standard deviation, and relative standard deviation) for this study are provided in Appendix E.

Results and discussion

Clay body of the Qingbai ware

A total of 43 Husi kiln ceramic ware bodies were analysed (Appendix B) and compared with data from two recent publications of comparable wares from Jingdezhen's Hutian kiln (Wu et al., 2020; Wang et al., 2020) (Appendix D).

Figure 6 clearly shows that the Husi Qingbai bodies have a higher $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio compared to Jingdezhen Hutian Qingbai ware (avg. $0.34 > 0.23$), which points to their greater refractoriness (Kerr and Wood 2004). Since the higher Al_2O_3 permits the clay body to be fired at a higher temperature (Cheng et al. 2006), this suggests that the Husi kilns could have fired their wares at a higher temperature, although a degree of underfiring might also have been tolerated or preferred.

Comparison of Na_2O and K_2O also highlights differences between the Husi and Hutian kilns. The K_2O composition of the Hutian kiln samples (avg. 2.98%) is much lower than that of the Husi kiln samples (avg. 4.21%), but the Na_2O content of Hutian kiln wares (avg. 1.22%) is nearly nine times more than that of the Husi kiln ceramics (avg. 0.17%). There are two principle mineral sources of potassium: potash feldspar and sericite (potassium mica), the latter being by far the more important in southern Chinese high-temperature ceramics. If ceramic production at Husi owed much to a southern influence, then the high level of potassium noted here should equate to high levels of sericite. In porcelain stone proper (i.e. derived from weathered granitoids), sericite increases due to the weathering of feldspar which also leads to a loss to solution of the sodium feldspar component. This would be a possible explanation for the lower soda values at Husi. However, the quantities of sericite (calculated from the corresponding wt% K_2O values) show the Husi bodies have more sericite than typical porcelain stone.

However, as confirmed by reference to local geological fieldwork and regional geochemical studies, we know that the Husi bodies were not based on the weathered granitoid-based porcelain stone that typifies southern production, as seen at Jingdezhen, for example. Geologists have long used selected trace element ratios as a reliable means of

Fig. 7 Nb/Ta–Zr/Hf ratio scatter plot for the clay bodies of Qingbai ware samples from Jingdezhen Hutian and five kilns of the Hushi kiln site, Fushan, Tuyuan, Wangma, Xiasi, and Yangji-axie. The trace element data of Hutian Qingbai ware ($N=11$) is from Wang et al. (2020)

Fig. 8 Fe_2O_3 content of samples from Wangma kiln layers 1–3 drawn against samples from Jingdezhen Hutian kiln. The TFe_2O_3 data for the Jingdezhen Hutian Qingbai ware ($N=14$) is from Wu et al. (2020) and Wang et al. (2020)

differentiating geological territories in such as those dominated by igneous rocks (igneous provinces). Since this approach also extends to understanding geochemical transformations in weathered rocks, it provides a powerful tool for the characterization and provenance determination of ceramic clays and porcelain stone.

Previous studies (Ding et al. 2013; Gelman et al. 2014; Wang et al. 2020) have highlighted the Nb–Ta and Zr–Hf ratios as good indicators for distinguishing raw material from different regions because their ratios would not be affected by the pedogenesis and weathering process of the parent rock. Figure 7 shows that the ratios of Nb/Ta and Zr/Hf of the Jingdezhen Hutian Qingbai ware ($\text{Nb/Ta}=3.6\text{--}5.4$, $\text{Zr/Hf}=10.0\text{--}12.3$) are much lower than those of the Hushi Qingbai ware ($\text{Nb/Ta}=7.1\text{--}18.6$, $\text{Zr/Hf}=10.0\text{--}44.8$). The samples from Yangji-axie and Xiasi kilns are different, but they are grey-greenish ware and not Qingbai ware. The grey-greenish ware from the Yangji-axie kiln has the highest Nb/Ta and Zr/Hf ratios observed, showing that their paste and glaze formula differ markedly from that of Qingbai ware.

It is also worth noting that the Nb/Ta and Zr/Hf ratio data show differences between different kilns at Hushi. Wangma kiln ($\text{Nb/Ta}=9.7\text{--}16.3$, $\text{Zr/Hf}=10.0\text{--}23.2$) and Fushan kiln

($\text{Nb/Ta}=7.2\text{--}21.2$, $\text{Zr/Hf}=20.1\text{--}44.8$) have significantly different Nb/Ta and Zr/Hf ratios even though the distance between these two kilns is less than 3 km. As mentioned above, Wangma and Fushan kilns are the only two excavated Qingbai ware kilns at Hushi. Based on typological analysis, wares from both sites are found to be similar in shape, colour, and style and have suggested that these two kilns may have been active at the same time (Northern Song Dynasty, 960–1127 AD) (Liu et al. 2016). The differences in Nb/Ta and Zr/Hf ratios that we now observe for these two kilns may either be due to the use of different raw material sources or the use of a common clay that varies naturally over short distances. This is an important point to clarify since it signifies either the intentional selection of different clays at the two kilns or a general acceptance of a non-uniform raw materials. Further field and laboratory research will be needed to throw light on the differences between the raw used at Hushi's kilns, both to understand the reasons behind them and to compare the operative level of quality control with that at Jingdezhen and the other Qingbai kilns. The ICP-LAS data also shows that the TFe_2O_3 content of the Qingbai ware from the earliest layer at Wangma is much lower than that of samples from the later layers, with the latter being

similar to the Hutian Qingbai ware in terms of their TFe_2O_3 (Fig. 8). Wood (2011) noted that a reduction in iron content usually means more sieving and processing of the raw material, though in the case that Wood cites for porcelain stone sieving removes iron but not Al_2O_3 . If sieving time or efficiency at Husi had decreased over time, then there would be less removal of quartz (SiO_2), and both Al_2O_3 and TFe_2O_3 would be reduced as SiO_2 increased. The material of the Husi Qingbai ware clearly behaves differently, again reinforcing the view that the Husi kilns were not based on the typical Southern Chinese porcelain stone of the type referred to by Wood in his example. Less sieving would also indicate less time investment, either because the chosen raw material did not require it or because of a lessened concern with quality. As mentioned above, the quality of the ceramic products from Wangma kiln becomes increasingly better as the stratum formation deepens. It thus seems that the paste processing at Wangma kiln worsened over time. One possible reason for this was that the kiln deliberately stopped producing high-quality Qingbai wares, perhaps due to changes in the target market or due to the exhaustion of high-quality raw materials. Exhaustion of raw material leading to the decline of a kiln is a known phenomenon; for example, the Yue kiln complex (one of the most famous celadon production centres before the Song Dynasty) is thought to have declined primarily because of a lack of wood for making wood ash, which is the essential raw material for producing the Yue lime glaze (Wood, 2011).

Previous studies (Wang et al. 2020; Zhu et al. 2010) found that Nb/Ta and Zr/Hf ratios of some high-quality Qingbai wares from Xicun kiln in Guangxi province are different from local low-quality Qingbai ware but similar to wares from Jingdezhen Hutian. They therefore deduced that these high-quality Qingbai wares had been produced at Hutian and were then brought to Xicun. However, our comparison of clay body sample data shows that the ratios of Nb/Ta and Zr/Hf of samples from Jingdezhen Hutian and kilns at Husi that produced high-quality Qingbai ware such as Wangma kiln and Tuyuan kiln differ markedly (Fig. 7). Unlike at Guangxi Xicun kiln and Dehua kiln where Qingbai ware from Jingdezhen clearly preceded the establishment of the local kilns, at Husi there is thus no indicator for a presence of Qingbai ware from Jingdezhen. The origin of the production technology for Husi Qingbai ware, which previously had been suggested to have come from Jingdezhen, thus needs further consideration.

Husi Qingbai glaze

Thirty-two Husi glazes were analysed (Appendix C).⁵ Again, for context, these were compared against published glaze data from several other Qingbai ware kilns including Jingdezhen Hutian kiln (Wu et al. 2020; Zhu et al. 2020), Fujian Dehua kiln, Huajiashan kiln, and Mingqing kiln (Xu et al. 2019). Previous studies have shown that it is difficult to distinguish the Husi Qingbai ware from that of the Dehua kiln in Fujian Province, because they have similar major elements in the glaze and are similar in their overall appearance (Chen et al. 1992). The present study aims to address this difficulty by using trace elements to supplement the major element geochemistry of these contemporary wares. Following the same pattern as for the clay body, the $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios and K_2O contents of Husi Qingbai glazes are higher than those from Hutian, while the Na_2O content is typically lower (Fig. 9). This might suggest that the same base clay was used for the ceramic body and glaze, an important point since the use of the body clay in the glaze is recognized as a southern tradition. Figure 10a, displaying scatter plots of Zr and Th, shows differences between samples from Qingbai ware kilns in Fujian, Jingdezhen, and Hubei. The Jingdezhen Hutian kiln has the lowest Zr and Th content, and the Dehua kiln has the highest Th content. The Zr and Th contents of products from Husi are mostly in the middle of the scatter plot. The Zr and Th contents clearly show the distinctiveness of Husi Qingbai glazes compared with products from other kilns.

Above, it was mentioned that there are notable differences in Zr/Hf and Nb/Ta ratios of clay bodies between the Wangma and Fushan kilns even though they are located close to each other. Nevertheless, as Fig. 10b shows, the distribution of Zr/Hf and Nb/Ta ratios of the glaze of Husi Qingbai ware from all kilns shows less scatter than bodies. On these graphs, the ratios of Husi grey-greenish ware and greenish ware can be clearly distinguished from the Husi Qingbai ware; this distinctly shows the glaze formula differences between various ware types. It seems that Qingbai ware from different kilns at Husi share the same raw material source and the same glaze formula.

Also notable is that samples from different layers at Wangma show differences in trace element data. As mentioned above, the Fe_2O_3 content in the clay body is higher in later products which may indicate a shift in production techniques. Differences in the main trace elements such as Sr and Ba between the early and later products (Fig. 11) confirm this hypothesis. A change in glaze formula, if shown to have

⁵ The glaze layer of some samples is too thin. Some spots were ablated on the middle layer of clay body and glaze instead of the glaze layer. The calcium data of these samples shows as abnormal.

Fig. 9 $\text{Al}_2\text{O}_3/\text{SiO}_2$ - K_2O and Na_2O scatter plots for the glaze of Qingbai ware sample of Jingdezhen Hutian and three Husi kilns (Fushan, Tuyuan, and Wangma). The major element data of Jingdezhen Hutian Qingbai ware ($N=18$) is from Wu et al. 2020

been intentional, may indicate the exhaustion of raw materials or the shift of the sales target (Cao 1998). For instance, Jingdezhen kiln changed the clay formula in the later period due to the exhaustion of kaolinite (Qin 2013). Reports on archaeological work at Husi note that clay sources around the kilns have not been exhausted (Liu et al. 2016; He et al. 2000; Wuhanishi et al. 1998). If these reports are confirmed by forthcoming field geology, then the reason for the change in Husi glaze recipes is unlikely to have been the exhaustion of clay raw material but perhaps socio-economic factors where the main driver for change.

Source of lime for Husi Qingbai glazes

The source of lime flux used in Chinese lime glazes can be from two contrasting raw materials: wood ash and burnt limestone (Ma et al. 2014; Ma et al., 2018; Wu et al. 2020). $\text{CaO}/\text{P}_2\text{O}_5$ and CaO/MgO ratios can help distinguish between wood ash glaze and limestone glaze (Ma et al. 2014; Wu et al. 2020). Wu et al (2020) note that the ratio of $\text{CaO}/\text{P}_2\text{O}_5$ and CaO/MgO is lower if the glaze was manufactured using wood ash, and the ratio is higher when the flux used is limestone.

This study determined $\text{CaO}/\text{P}_2\text{O}_5$ and CaO/MgO ratios for Husi Qingbai ware samples and compared these with published data from Fanchang, Dehua, Minqing, Jingdezhen Hutian, and Jingdezhen Lantian kilns (Wu et al. 2019; Wu et al. 2020; Xu et al. 2019; Yang et al. 2010). The comparison (Fig. 12a) shows both the $\text{CaO}/\text{P}_2\text{O}_5$ and CaO/MgO ratios of the Husi Qingbai wares to be the lowest with no apparent tendency to change over time or between wares. In contrast, the wares from other kilns, with the exception of Dehua kiln which has too little data to allow for estimating trends, all show a clear trend of increase both in $\text{CaO}/\text{P}_2\text{O}_5$ and CaO/MgO ratios (Fig. 12b and c). This probably means that the collected materials from Wangma, Tuyuan, and Fushan kiln had not seen a change in glaze formula from botanic ash to limestone based even though some of them show a high quality similar to that of wares from Jingdezhen.

The reasons for this conservative glaze practice are not entirely clear. The change from using wood ash to using seen elsewhere for producing Qingbai glazes does not seem to have reached the Husi kiln complex or was not adopted there for other reasons. Perhaps the three Qingbai ware kiln sites from which the article draws its material were abandoned before the new glaze recipe came to be used? In any event, the current data shows no evidence of the use of limestone

Fig. 10 (a) Zr-Th scatter plot for the glaze of Qingbai ware from Jingdezhen Hutian kiln, Husi kiln site, Huajiashan kiln, Mingqing kiln, and Dehua kiln; **b** Nb-Ta-Zr/Hf ratios for the Jingdezhen Hutian Qingbai ware and three different types of products of the Husi kiln site (greenish ware, grey-greenish ware, and Qingbai ware). The trace element data of Hutian Qingbai ware is from Wang et al. (2020); the data from Dehua, Huajiashan, and Mingqing ($N=41$) is from Xu et al. (2019).

glaze at Husi. Tentatively this could be an indicator that the Husi Qingbai ware may date no later than the end of the Northern Song Dynasty. However, there are 123 other Qingbai ware kilns at Husi, and the data from three kilns cannot provide exhaustive evidence for the site as a whole. This situation requires more samples from other kilns to be analysed to check the various hypotheses just suggested.

Grey-greenish ware

Again, for production context, the Husi grey-greenish wares were also compared against similar products from the Jingdezhen Lantian kiln. Visual comparison showed these to be very similar, both with a brown-green glaze on a thick grey clay body, leading to the suggestion that they conformed to a similar aesthetic and style and that they may have been contemporaneous. The chemical analyses, however, shows that the green-greyish wares from these two production centres were very different in composition. As Fig. 13 shows, the $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio of the glaze of products from Yangjiaxie kiln is higher than that of wares from Jingdezhen Lantian kiln (avg. $0.3 > 0.21$). The Al_2O_3 content of the Yangjiaxie grey-greenish ware body is over 18% and thus higher than that of wares from Jingdezhen Lantian (Fig. 13). The K_2O

and Na_2O content are similar for products from both kilns, and the Lantian kiln has a lower TiO_2 and higher MgO content.

However, the most notable difference between these two kilns is that the CaO content of Jingdezhen Lantian glazes (avg. 14.42%) are considerably higher than those observed on samples from Yangjiaxie (avg. 4.15%), and the Fe_2O_3 contents is correspondingly much lower (avg. $2.13\% < 8.29\%$). This cannot be an analytical artefact produced by laser-ablating the intermediate layer of body-and-glaze instead of the glaze layer because the Fe_2O_3 content of the clay body is much lower than that of the glaze (avg. $3.12\% < 8.29\%$) (Fig. 14).

The fact that the glaze of Yangjiaxie grey-greenish ware was based on iron-rich material confirms that Yangjiaxie and Jingdezhen Lantian did not share a similar glaze formula but used different ceramic processing technologies despite being similar in appearance. This may mean that Husi and Jingdezhen started firing ceramics independently from each other at roughly the same time (around the mid-late period of the Tang Dynasty). Clearly, the Husi kiln complex used a different type of raw material for the body than was customary at southern kilns such as Jingdezhen and also employed a different glaze recipe for their Qingbai and Grey-greenish

Fig. 11 Sr and Ba box plots for Jingdezhen Hutian Qingbai ware and Wangma Qingbai ware. The Sr and Ba data ($N=21$) are from Wang et al. (2020)

wares. While the precise nature of the raw materials used at Husi needs to be investigated further, the evidence so far points to a ceramic technology that was by no means entirely derived from Jingdezhen but much more independent than previously thought.

As to the unusually high iron content, iron usually serves as a colourant for the glaze, and it also has a fluxing effect (Kerr and Wood, 2004), but such a high iron oxide content is rare. According to Wood (2011), the highest iron content observed in the glaze of Chinese ceramic products is around 6% as seen in the black glazed ceramic products of the Cizhou kiln and Jingjing kiln in the Hebei Province, where the potters added loess when manufacturing the glaze. The average iron oxide content of grey-greenish ware from Yangjiaxie is 8.39%. Such a high iron oxide content has never been observed in any ceramic product from any other kiln site in China. This raises many questions and, given the potential significance of this observation, requires verification by a second, independent technique.

SEM–EDS analysis for Husi grey-greenish ware

To verify the unusually high iron content measurements for grey-greenish ware from Husi Yangjiaxie kiln, this study

applied SEM–EDS (scanning electron microscopy with energy dispersive X-ray spectroscopy) to observe the iron oxide distribution within the glaze. The analysis for the grey-greenish ware samples was performed at the Scanning Electron Microscopy Laboratory of the Suzhou Institute of Nano-Tech and Nano-Bionics (SINANO) at the Chinese Academy of Sciences. The analysis was conducted using a Quanta 400 FEG scanning electron microscopy (SEM) at 20 kV. Energy-dispersive spectroscopy (EDS) measurements were performed on the Quanta 400 FEG SEM at 20 kV for analysing the composition of selected areas.

The white irregular crystals around the glaze part visible in Fig. 15a are iron oxide crystals, and their presence could suggest the potential for a possible experimental error (i.e. an elevated and non-representative iron oxide measurement) had the laser-ablation spots coincided with areas where these iron oxide crystals are concentrated. Yet, even selecting an area where there are almost no such crystals for elemental analysis mapping (red square in Fig. 15a) gave a Fe content of 12.78% which matches the LA-ICP-MS analysis results. Furthermore, we analysed another grey-greenish ware sample that has a clear glaze phase (Fig. 15b). The results show that the iron oxide content is 7.65% which matches the results of the previous analysis.

Fig. 12 (a) CaO/MgO–CaO/P₂O₅ scatter plot for the glaze of Qingbai ware samples from Jingdezhen Hutian kiln and Lantian kiln, Husi kiln group site, Dehua kiln, Mingqing kiln, and Fangchang kiln; (b) clustered line plot of the CaO/P₂O₅ ratio value; (c) clustered line plot of the CaO/MgO ratio value. The data from Lantian and Hutian kiln samples was taken from Wu et al. (2020); the data of Mingqing kiln was obtained from Wu et al. (2019); the data of Dehua kiln is from Xu et al. (2019); the data of Fangchang kiln data is from Yang et al. (2010).

Although the SEM–EDS, as used in this study, is a semi-quantitative method of chemical analysis, it showed almost the same result as the LA-ICP-MS analysis conducted on the same

samples. The extraordinarily high iron content of the Husi grey-greenish ware has thus been verified by two independent methods of analysis, and the results clearly show that Husi

Fig. 13 Clustered line plot of the major element for grey-greenish ware samples from Jingdezhen Lantian kiln and Husi Yangjiaxie kiln. The major element data of the Jingdezhen Lantian grey-greenish ware ($N=15$) is from Wu et al. (2020)

Fig. 14 CaO and Fe₂O₃ content box plots for the both clay body and glaze of grey-greenish ware from Husi Yangjiaxie

potters used particularly iron-rich material in their glaze recipe to produce grey-greenish ware. This is in marked contrast to their counterparts from their Jingdezhen counterparts which used true lime glazes with much more moderate levels of iron.

Conclusion

This paper set out to reach three objectives: (1) to make a methodological contribution by combining typological research and scientific analysis which are usually the

subject of separate papers, (2) to compare products and production processes and raw materials from Husi to their more well-known counterparts from Jingdezhen, and (3) to fingerprint the Husi ceramic products to provide data that can be used in future comparative research, allowing us to identify Husi kiln products traded to other locales. Below, the results for each of these three objectives are outlined, and avenues for future research are set out.

Fig. 15 Elemental mapping analysis for grey-greenish ware samples from Husi Yangjiaxie kiln site via SEM-EDS analysis. The results confirm that Husi Grey-greenish ware has an extraordinarily high iron

content that exceeds all previously reported ceramic product from pre-modern China

Combining typological research, archaeological observations, and scientific analysis

The typological analysis and archaeological observations discussed above find both northern and southern characteristics represented in production at the Husi kiln complex. Most kilns at Husi are the dragon kiln type typical of southern ceramic production. The bulk chemical analysis illustrates that the early Qingbai ware from Wangma kiln applied a glaze formula similar to that used at the Jingdezhen as reflected in similar key minor and trace elements such as Fe, Sr, and Ba.

Also, the kiln tools and celadon products from Xiasi kiln have been shown to resemble those from Yaozhou kiln which is one of the major northern kilns. The discovery of kiln-spurs and thicker glaze celadon at Xiasi kiln indicates that the celadon production technology may have reached Xiasi kiln site during the Five Dynasties period coming from Yaozhou and Huangbao kilns in the north. The compositional analysis also highlights differences between objects produced at Xiasi and other kilns even though they are all the part of the Husi kiln complex.

The considerable dimensions of some of the kilns at Husi are a typical feature of southern Chinese ceramic production, but the use of kiln-spurs, as well as thicker glazed celadon, is a northern feature. Although tentative,

this combination of certain southern and northern features, if supported by ongoing excavations, could make the Husi kiln complex a possible intermediary between southern and northern ceramic traditions. This potential highlights the importance of Husi and need for future research on the site and its ceramics.

Additionally, Husi seems to have had particularities of its own. For instance, the grey-greenish ware of the Yangjiaxie kiln outwardly exhibits very similar characteristics to that of the Jingdezhen Lantian kiln. However, the Husi grey-greenish ware shows a high iron oxide content that exceeds the levels observed with any other known ceramic types from other kiln sites (av. 8.39%). This clearly shows that the Husi kiln complex had its own glaze recipe, in this case producing a green glaze using high levels of iron in reduction, and not based on the lime glazes that typify southern production. From typological comparisons with securely dated finds from other sites, the grey-greenish ware found at Husi probably dates to the Tang Dynasty. However, given the considerable lengths of that period and the particularities of the glaze formula used in the production of grey-greenish ware at Husi, further fieldwork and comparative stylistic as well as technological and geochemical analysis will be needed to assess the date of production of the different types of wares at Husi, as well as its relations with other contemporary as well as earlier and later sites.

Connections between Husi and Jingdezhen

During its early period of usage, potters at the Husi kiln complex may have been in contact with potters at Jingdezhen as reflected in similarities in key trace element content of the early Qingbai ware products from Husi with wares from Jingdezhen. A comparison between early and later products of Wangma kiln has shown that the former may share a similar glaze formula with Jingdezhen wares, but the glaze formula changed in the later periods as reflected in its distinctive trace element composition. The reason for this unusual shift from higher to lower quality rather than the other way around may have been a shift in sales target from selling a smaller number of higher-priced items to a more exclusive audience to producing a larger number of cheaper wares for a broader range of customers. Another possible explanation would be that high-quality Qingbai production may have been short-lived because there was a limited availability of purer raw materials and material depletion, thus forcing a shift from higher to lower quality. Further research into local raw material availability as well as ceramic consumption and trade will be necessary to decide this matter.

Another important observation made in this study is that the trace element data highlight differences in the clay body of Qingbai wares from different kilns in the Husi kiln complex. This indicates that either that several clay sources were being used at Husi or a common clay that varied naturally over short distances: further fieldwork is currently being undertaken to resolve this. Moreover, the high alumina content and lower soda values combined with higher than expected levels of potassium and sericite suggest that the raw material used for producing the clay bodies at Husi cannot have been the typical porcelain stone (in the sense of weathered Yanshanian granitoids). The combination of a lower iron content with a higher aluminium content is not a feature of *petunse* porcelain stone, which indicates that the Husi kilns were using a different raw material than at Jingdezhen to produce their ceramic body.

Fingerprinting the Husi kiln products

This study has analysed chemical compositional data of both Qingbai ware and grey-greenish ware from the Husi kiln complex, comparing wares from different kilns at Husi with each other as well as with published compositional data from other major ceramic production centres. Both major and trace elements clearly set the Husi Qingbai ware apart from the Jingdezhen Qingbai ware. Qingbai ware from the Husi kiln has similar major elements to that of the Dehua kiln in Fujian Province, but the trace element ratios (Zr/Th and Ta/Nb) differ. These trace elements ratios can be used as a fingerprint for discriminating Husi Qingbai ware from similar ceramics produced by other kilns.

As discussed above, the Ca/MgO and Ca/P₂O₅ ratios of the Husi Qingbai ware glazes are lower than Qingbai wares from any other kiln where wares have undergone analysis so far. This suggests that potters firing their wares in the Husi kilns under consideration here did thus not use limestone in their glazes. The extremely low Ca/MgO and Ca/P₂O₅ ratios in Qingbai wares may mean that Husi potters applied a type of plant ash that was different from that employed at other kilns where wares have been analysed so far. Further comparative analysis and experimental work with different types of plants and glaze recipes would be helpful in exploring this point further.

The fingerprint established for the Husi products can be used as a basis for exploring their target market and customer base as well as the trade networks that connected them. The paper has also thrown some light on notable differences between individual kilns at Husi in terms of choice of raw-material sources and hence production techniques and target markets and maybe also date.

Further field research aiming to explore these differences further is currently already under way. Further laboratory research is also needed to understand the ramifications of the extraordinary iron content of the Husi grey-greenish ware. The present paper has thus provided new insights as well as a considerable number of new questions that will be explored in future research both by the authors of this piece and hopefully many other scholars.

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Code availability All statistical analyses were conducted using SPSS. No coding was involved.

Declarations

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