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Koryŏ inlay celadon from Taicang Port of the Yuan Dynasty, China

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Abstract

Inlay celadon was a type of high-end ceramics of the Koryŏ dynasty (918–1392 AD) produced in the Korean Peninsula. It was conveyed to China during the Yuan dynasty (1279–1368 AD) as tribute or trade goods. In this study, the authors analyzed six samples of inlay celadon recently discovered at the prosperous Taicang Port of the Yuan and Ming dynasties in the lower Yangtze River, China. With scanning electron microscopy coupled with energy dispersive spectroscopy (SEM–EDS) and X-ray diffraction (XRD), the authors investigated the production technique, and compositional characteristics of these samples for the purpose of tracking their provenances. While the bodies are made of porcelain stone, the glazes are of porcelain stone and calcium-rich flux. The white inlay material in these samples is kaolinite-dominant, and the black one is made of quartz with high Fe content or a compound of quartz and raw materials with high Fe content. The results link the samples uncovered at the Taicang Port to the Samhŭngni Kiln in Kangjin-gun and the Uch'ŏlli and Chinsŏri Kilns in Buan-gun in Southern Korea. The products from these kilns were shipped to China in several shipments.

Keywords Yuan dynasty, Taicang Port, Koryŏ inlay celadon, Sino-Korean interaction, Scanning electron microscopy

Introduction

Celadon, with a variety of colors of glaze, was a major type of ancient ceramics in China, and the most eminent products were those of the Yue (first-eleventh centuries AD), Longquan (tenth-sixteenth centuries AD), and Yaozhou (seventh-fourteenth centuries AD) kilns. The ever-flourishing exportation of Chinese celadon wares to East Asia and Southeast Asia since the Six Dynasties (222-589AD), inspired the ever-growing imitation of them in these regions. In Japan, true celadon was created only in the seventeenth century [1], before which lead-glazed and gray-glazed wares that emulate the Yue and Longquan celadons were produced in the ninth-sixteenth centuries [2]. In the eleventh-fourteenth centuries Vietnam, the main target of imitation was the Yaozhou celadon [3]. The glaze of the products is mainly green, but quite volatile and opaque, the body sloppy, and the bottom applied with "iron juice", one of the important characteristics of Vietnamese porcelain [4]. In Thailand, imitations of Longquan wares were manufactured after the fourteenth century [5].

In the Korean Peninsula the production of ceramics developed rapidly during the Koryŏ dynasty (918–1392 AD) upon the inspiration of the Yue Kiln in southeast China, culminating in the rise of celadon and the creation of "emerald celadon" and inlay celadon. Koryŏ inlay celadon, in particular, is distinctive in that white and/or black materials are inlaid into pre-carved patterns upon the surface of dark-colored body before transparent celadon glaze is applied. As commented by Cao Zhao (late Yuan and early Ming dynasties) in his *Essential Treatises on Antiquities*, "the ancient Koryŏ wares are bluish green and similar to the Longquan wares; the ones that are decorated with white flower petals are not very valuable

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[6]". The beginning of the Koryŏ inlay celadon, which this passage refers to, is yet undetermined. The earliest dated item is a bowl found in a tomb of Mungoongyu (1159 AD) near Kaegyeong [7], and for this reason the production of this ware is often thought to be started in the mid-twelfth century [8]. The origin of the inlay technique, without excluding the possibility of northern China, where the technique in ceramics was invented around the tenth century, was likely borrowed from Korean silverware and lacquerware [9]. This technique was subsequently disseminated to Kangjin-gun in Jeolla-nam-do, and Buan-gun in Jeolla-buk-do.

The Koryŏ inlay celadon has also been discovered in a number of kilns. It was first discovered at the Bangsandong and Sŏri kilns in Gyeonggi-do [10]. At the Sŏri Kiln, which was excavated three times from 1984 to 1988 by the Hwaam Museum of Art, fragments of the mid-ninth century were found. At the Bangsandong Kiln, which was excavated in 1997 by the Haegang Ceramic Museum, a small number of fragments of the second half of the tenth century were uncovered. During this early period the production was small in scale, the product was monotonous in form, mostly waist drum, and the decoration was crude. Since the late tenth century, the production was shifted to Kangjin-gun in Jeolla-nam-do, and Buan-gun in Jeolla-buk-do, which gave rise to a plethora of outstanding kilns at Yangjaeni in Hampyeong-gun (tenth-eleventh centuries), Chinsanni in Haenam-gun (late tenth-eleventh centuries), Yonggunni (late tenth-eleventh centuries), Samhŭngni (late eleventh-mid twelfth centuries), and Sadangni (twelfth-fourteenth centuries) in Kangjin-gun. It was continued at the Chinsŏri Kiln (second half of the twelfth century-thirteenth century) and Uch'ŏlli Kiln (twelfth-fourteenth century) in Buan-gun. After the fourteenth century, the production of this ware declined, only occurring at the two kilns of Suyudong (1380-1420AD) in Seoul and Hwangjini in Gyeongsang-buk-do (mid-fourteenth-mid-fifteenth centuries). In this last period, inlay celadon remained to be the mainstream product of the kilns; a new technique for preparing the grooves for inlay, stamping motifs on the surface, was employed to enhance the production efficiency, denoting the increasing popularity and decreasing quality of Koryŏ inlay celadon [11].

In recent years, modern quantitative chemical analyses are increasingly used in the studies of production technique and provenance of Koryŏ celadon [12], the technical connection between this ware and the Yue celadon, the provenance of the items uncovered from the seabed of Wonsan Island in Korea, and the coloring mechanism of the glaze of this ware. Kyung Nam Kim and Sung Jin Kim analyzed Koryŏ celadon shard's body, glazed and inlay from tenth to fourteenth century [13]. Kyong-Shin Carolyn Koh's team, discovered that Koryŏ celadon has higher concentrations of MnO and lower concentrations of TiO_2 than Yue and Longquan celadon [14]. Emi Koseido found zircon to be the elemental fingerprint of the bodies and glazes of the Koryŏ celadon wares [15]. Pamela Vandiver, based on a comprehensive analysis of glazes of Koryŏ emerald celadon and inlay celadon wares from 40 kiln sites in Kangjin-gun and Buan-gun, concluded that the low-aluminum and high-calcium glazes of Koryŏ inlay celadon resonate with those of the Yue, Guan, and Longquan wares; the main constituent for the white fill is quartz, and the black fill is stonepaste made of magnetite crystal and quartz [16]. Seung Wook Ham et al. discovered that porcelain stone, weathered rock comprised of quartz, mica, and feldspar, is the raw material for the bodies and important component of the glaze and white fill, and black fill is a modification of the glaze by adding colored minerals such as biotite with high iron content [17].

Given the current state of research on Koryŏ celadon and inlay celadon, however, the production process and compositional characteristics of this ware have not been examined. In this study, six samples of Koryŏ inlay celadon were collected from the Yuan dynasty (1271–1368AD) Taicang Port in Jiangsu Province, China, to approach the two questions. For the sake of provenancing these samples, the existing compositional data of samples from several kilns in Kangjin-gun, Buan-gun, and the City of Daejeon in Southern Korea, were utilized. For the sake of understanding the temporal and spatial scopes of the trade of Koryŏ inlay celadon, compositional data of celadon samples from the Palace Precinct of the Southern Song dynasty (1127–1279AD) in Hangzhou, China, were also acquired for the use of this study. A note is due that fragments of the Koryŏ celadon and inlay celadon discovered at the two sites are rather modest in quantity, but they provide a unique opportunity for this study.

The samples

The Taicang Port was discovered at the Fancunjing site in the west of Fanjing village, Taicang City, China in the lower Yangtze River (Fig. 1). From January 2016 to December 2017, at the call of a construction project, a total area of about 13,000 square meters was excavated, and a set of storage facilities, roads, riverbeds, and a bridge were discovered, and about 150 tons of fragments of celadon wares of the middle and late Yuan dynasty were retrieved [18]. The unexpected discovery of the ceramics, which have been identified as products of the Longquan, Jingdezhen, Cizhou, and Tiedian Kilns, at this port, reveals that it was a trade center for ceramics bound for both domestic and international markets.

Among the massive ceramics discovered at the Fancunjing site, the great majority are products of the Longquan

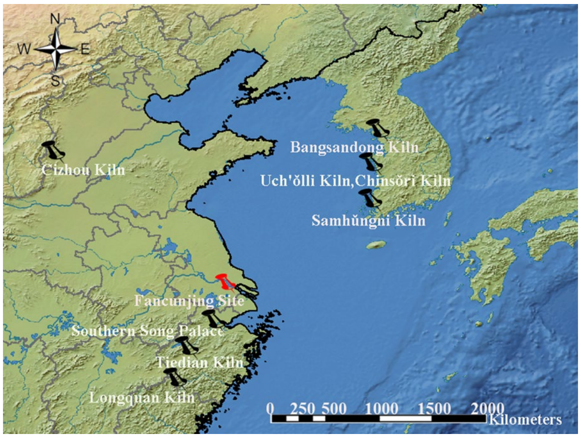


Fig. 1 Locations of sites and kilns

Kiln, but there are a small number of the Koryŏ inlay celadon, from which the authors collected six samples for this study. Overall, the samples are fragments of stemmed goblets, jars, or plates (Fig. 2). The bodies of these samples are grayish and fired hard. The glazes are brownish or grayish green. Most of the samples are decorated with flowers, petals, strings, dots, and circles. The motifs are rendered with white and black materials inlaid into precarved grooves and dins. The combined application of white and black lines, especially in the case of Sample TC-6, creates an illusion of deep carving, recalling the carved designs of the Yue celadon. From the appearance, it is clear that there are two groups: 1 and 3 are of high quality and the others are of low quality.

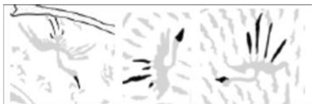
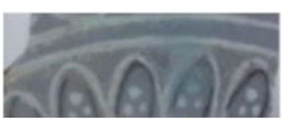
Koryŏ celadon wares were exported to China during the Southern Song dynasty. Among the ones that have been excavated from the Palace Precinct in Hangzhou, most are of the emerald celadon wares, the fact of which reflects the predilection of the Southern Song rulers for monochromic thin-bodied and thick-glazed ceramics. The discovery of the Koryŏ inlay celadon at the Fancunjing site denotes a continuous trade connection between Koryŏ and China in the Yuan dynasty, yet a shift of aesthetic taste towards ornate ceramics among Yuan bureaucrats, nobles, and members of the imperial family, the usual patrons for imported commodities, in this period.

Typological comparation

By analyzing the decorative techniques and motifs of Koryŏ inlay celadon, the provenance and chronology of Koryŏ porcelain can be initially established by

Fig. 2 Samples of Koryŏ inlay celadon from the Fancunjing site

Table 1 The detailed description of samples (images: Hong Fj. A study on the inlay decoration of Koryŏ porcelain. Master degree thesis, Jilin University, 2019; Lotis C, Lee DM, Symbols of identity: Korean ceramics from the collection of Chester and Wanda Chang, 2010, p.39; Shen QH, Exhibition of Koryŏ celadon wares from Gangjin of Korea, Beijing: Heritage Publishing House, 2012, p.88)

TC-1	 	The motif of crane first appeared in the twelfth century. Two representative kiln sites, which featured this motif, are Sadangni in Kangjin-gun, and Uch'ŏlli in Buan-gun. The crane motif from the Sadangni kiln site is bent at the end of its extended wings to form folded wings, and the neck of the crane is turned in parallel to the wings, expressing the crane's movement [19].
TC-2 TC-3		After the thirteenth century, the motif of circle was commonly used as ornamental band [20]. The circles with dots inside mimick fish eggs.
TC-4 TC-5	  	The motif of realistic chrysanthemum between the twelfth and fourteenth century was reduced to a pattern. This pattern was standardized during this period. The most representitive case comes from the Uch'ŏlli kiln site in Buan-gun [11]
TC-6		The lotus petal is one of the most popular motifs on Koryŏ inlay celadon. In the twelfth century, this pattern commonly appeared as minor decorative band on the mouth rim or bottom of the objects.

archaeological methods. The detailed description are shown in Table 1.

Analytical Methods

In this study, the authors employed energy dispersive X-ray fluorescence spectrometry (ED-XRF), X-ray diffraction (XRD), and scanning electron microscopy coupled with energy dispersive spectrometry (SEM–EDS) to analyze the composition and microstructure of the bodies, glazes, white and black fills of the six samples.

The X-ray diffraction (XRD) and SEM–EDS analyses were performed at the Nanjing Hongchuang Geological Survey Technological Service Co., LTD, and the State Key Laboratory of.Mineral Deposits Research, School of Earth Sciences and Engineering, at Nanjing University. The micro-area X-ray diffraction (XRD) analysis was performed on a Rigaku RAPID II X-ray diffractometer. The instrument was operated at 50 kV and 90 mA on a rotating Mo anode X-ray source. The XRD patterns of samples were collected with a two-dimensional image plate and a 9-min exposure time per analysis [21]. The samples were sliced, used a hard-tip pen to separate the white and black inlays in the samples and tested them separately; while the glaze and the body were not separated.

The model of scanning electron microscope used was TESCAN Mira3 LMH, and the BSE probe was produced by TESCAN Company. The samples were coated with conductive film before testing: the surfaces of the samples were scrubbed with anhydrous ethanol, blown dry with the ear wash ball after the alcohol was completely evaporated, and put into the carbon plating instrument for carbon plating film (10 nm film plating). Thereafter the samples were sent to the instrument for analyzing. The qualitative analysis of chemical elements was performed with X-ray energy spectrometer coupled with Oxford AZtec X-Max 150 X-ray Energy Spectrometer (EDS) under the working condition: acceleration voltage 15 kV, electron beam (focused beam) diameter 2-3um, data acquisition time about 60 s, dead time at about 60%.

The analysis of the composition of the bodies and glazes was undertaken at the Laboratory of Archaeological Science, School of Archaeology and Museology, Peking University. First, the samples were sliced. The instrument was XGT 7000 ED-XRF manufactured by the Precision Instruments Company (Horiba) of Japan, with an X-ray spot diameter of 1.2 mm, X-ray tube voltage of 30 kV, X-ray tube current of 0.029 mA, and data acquisition time of 100 s. The standby time was maintained below 30% [22]. The apparatus was calibrated with the Corning-D reference glass (Additional file 1: Table S1). The tested portion is a fresh cross-section of bodies of Koryŏ inlaid celadon, so the test results reflect the chemical composition, and the experimental equipment and conditions show that the glaze test does not penetrate the body, so it reflects the chemical composition and content of the glaze.

Results and discussion

Inlay technique

The authors analyzed the inlay technique of the six samples with scanning electron microscopy. As shown in Fig. 3, the authors were able to observe the microscopic structures of these samples. One can see that in Samples TC-1, TC-2, TC-3, TC-4 and TC-6, white material is inlaid into pre-carved patterns on the bodies to bear out the motifs before the glaze is applied; the carving is rough, and the fill is loose. Sample TC-4 is unique in that both white and black fills are present. The white fill of Sample TC-5 appears to be spread directly upon the surface of the body without the preparation of grooves. In each sample, the glaze seeps into the crevices of the loose white fill.

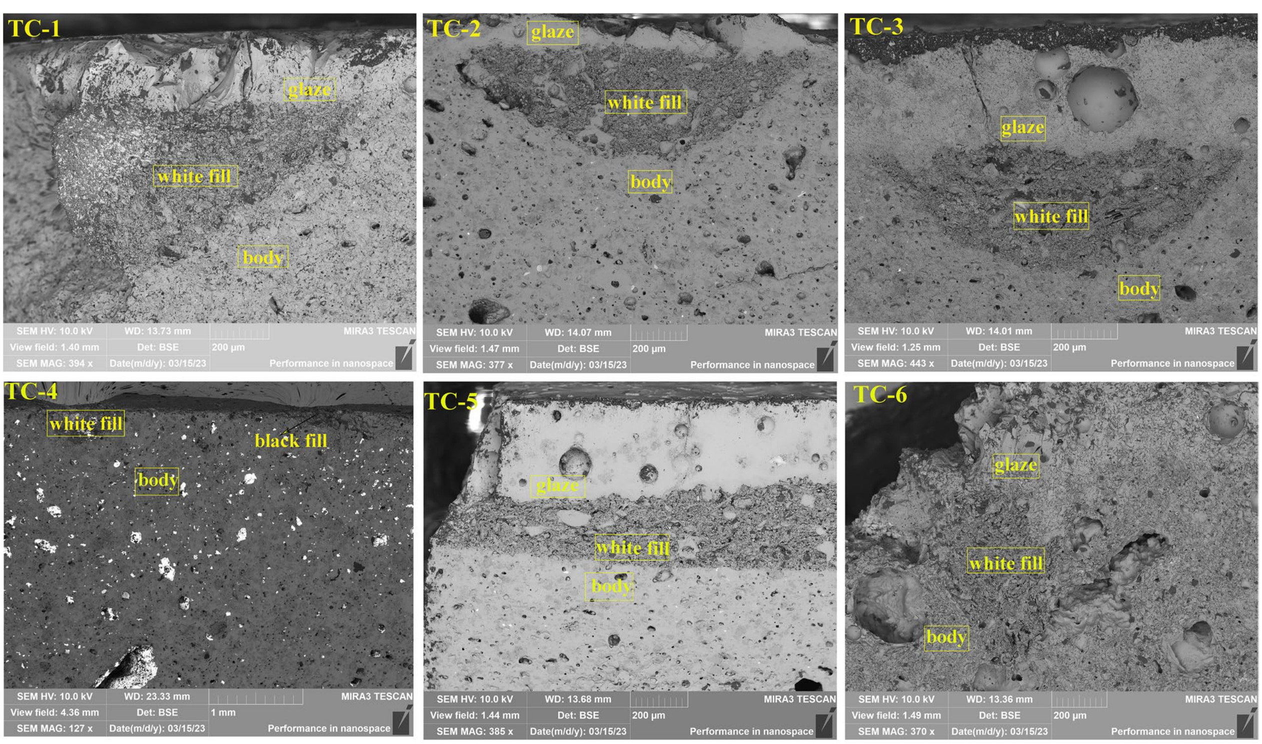


Fig. 3 Scanning electron microscopy images of the six samples

Table 2 Compositional data of the bodies, glazes, white and black fills of the six samples

Sample	Part	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3
	body	0.16	0.59	22.33	63.89	0.10	5.36	1.30	0.47	0.11	5.70
TC-1	white fill	0.00	0.16	33.54	53.59	0.01	4.75	1.92	0.77	1.00	4.27
	glaze	0.97	1.35	16.59	61.78	0.00	3.76	13.38	0.39	0.20	1.59
	body	0.83	0.55	13.62	78.49	0.00	3.59	0.48	0.59	0.00	1.84
TC-2	white fill	0.50	0.38	43.10	51.90	0.00	2.78	0.17	0.00	0.00	1.16
	glaze	0.84	2.21	15.02	61.81	0.94	3.22	13.82	0.15	0.44	1.55
	body	1.01	1.02	26.42	63.54	0.00	2.65	0.53	1.23	0.00	3.60
TC-3	white fill	0.70	0.17	41.82	53.08	0.00	2.78	0.26	0.00	0.00	1.09
	glaze	0.90	1.30	17.73	62.56	0.34	2.94	13.59	0.14	0.00	0.50
	body	1.69	1.12	19.69	68.20	0.00	3.83	0.63	1.66	0.00	3.19
TC-4	white fill	0.00	0.00	40.69	50.84	0.00	1.72	0.00	2.14	1.42	3.18
	black fill	1.32	0.73	19.93	67.55	0.06	4.57	0.80	1.14	0.82	3.08
	glaze	0.64	0.59	13.29	68.51	0.00	5.95	9.55	0.00	0.00	1.46
	body	1.11	0.52	13.49	78.59	0.00	3.35	0.39	0.65	0.00	1.90
TC-5	white fill	0.99	0.80	21.10	69.40	0.00	3.92	0.46	0.44	0.00	2.26
	glaze	0.54	0.75	13.43	69.40	0.00	4.57	9.91	0.00	0.23	1.18
	body	1.11	1.13	20.51	67.49	0.00	3.67	2.70	0.98	0.00	2.41
TC-6	white fill	0.78	0.47	41.27	50.96	0.00	3.45	0.34	0.19	0.00	0.09
	black fill	1.25	1.69	24.97	55.24	0.60	2.85	3.39	1.70	2.10	6.22
	glaze	0.62	1.96	15.57	61.06	0.62	3.14	14.69	0.36	0.42	1.55
	body-Ave	0.99	0.82	19.34	70.03	0.02	3.74	1.01	0.93	0.02	3.11
	body-1std	0.45	0.27	4.61	6.25	0.04	0.82	0.81	0.41	0.04	1.32
	glaze-Ave	0.75	1.36	15.27	64.19	0.32	3.93	12.49	0.17	0.22	1.31
sample	glaze-1std	0.16	0.58	1.59	3.41	0.36	1.05	2.00	0.15	0.18	0.38
	white fill-Ave	0.50	0.33	36.92	54.96	0.00	3.23	0.53	0.59	0.40	2.01
	white fill-1std	0.38	0.26	7.71	6.54	0.00	0.96	0.64	0.74	0.58	1.40
	black fill-Ave	1.29	1.21	22.45	61.40	0.33	3.71	2.10	1.42	1.46	4.65
	black fill-1std	0.04	0.48	2.52	6.16	0.27	0.86	1.30	0.28	0.64	1.57

Compositional characteristics of the bodies, glazes, and inlay materials

The authors used SEM–EDS to acquire the compositional data for the purpose of analyzing the bodies, glazes, white and black fills of the six samples. The data are shown in Table 2. Furthermore, the mineralogical analysis enables to identify the mineral phases that really influence the behaviour of the raw materials. X-ray diffractometry (XRD) allows the qualitative analysis of the various minerals and in technological studies on ancient ceramics, this type of analysis plays and important role [23]. The results are shown in Fig. 4.

As shown in Table 2, the Al_2O_3 contents of the bodies of the six samples fall within the range of 13.49–26.42%, and the SiO_2 contents within the range of 63.54–78.59%. The Al_2O_3 and SiO_2 contents, echoing those of porcelain stone that features low aluminum and high silicon in southern China, the XRD image show that the main crystalline component of the body of Sample TC-4 is mullite (Fig. 4a), which are commonly found in the bodies fired at high temperatures (1250–1500 °C).The Al_2O_3 contents of the glazes of the six samples are relatively lower, within the range of 13.29–17.73%, yet the SiO_2 contents vary from 61.06 to 81.31%, indicating that the glazes are made of mixtures of porcelain stone and flux. Porcelain stone are born as result of long-term hydrothermal process and weathering of a group of rocks such as pegmatite. The XRD image shows that the crystalline components of the glaze of Sample TC-4 is quartz (Fig. 4b). Tempered with fluxes CaO, Na_2O, K_2O, and MgO, they generate transparent glass, and improve the gloss of the glaze. The calcium contents of the glazes of the samples occur within the spectrum of 9.55–14.69%, indicating that they are coated with the calcium glaze.

The Al_2O_3 contents of the white fills of the six samples vary from 21.10% to 43.10%, and those of the four samples of TC-2, TC-3, TC-4 and TC-6 even higher, up to 40.69–43.10%, surpassing those of the bodies and glazes. The SiO_2 contents of the white fills range from 50.84% to 69.40%, and the Fe_2O_3 contents occur within the range

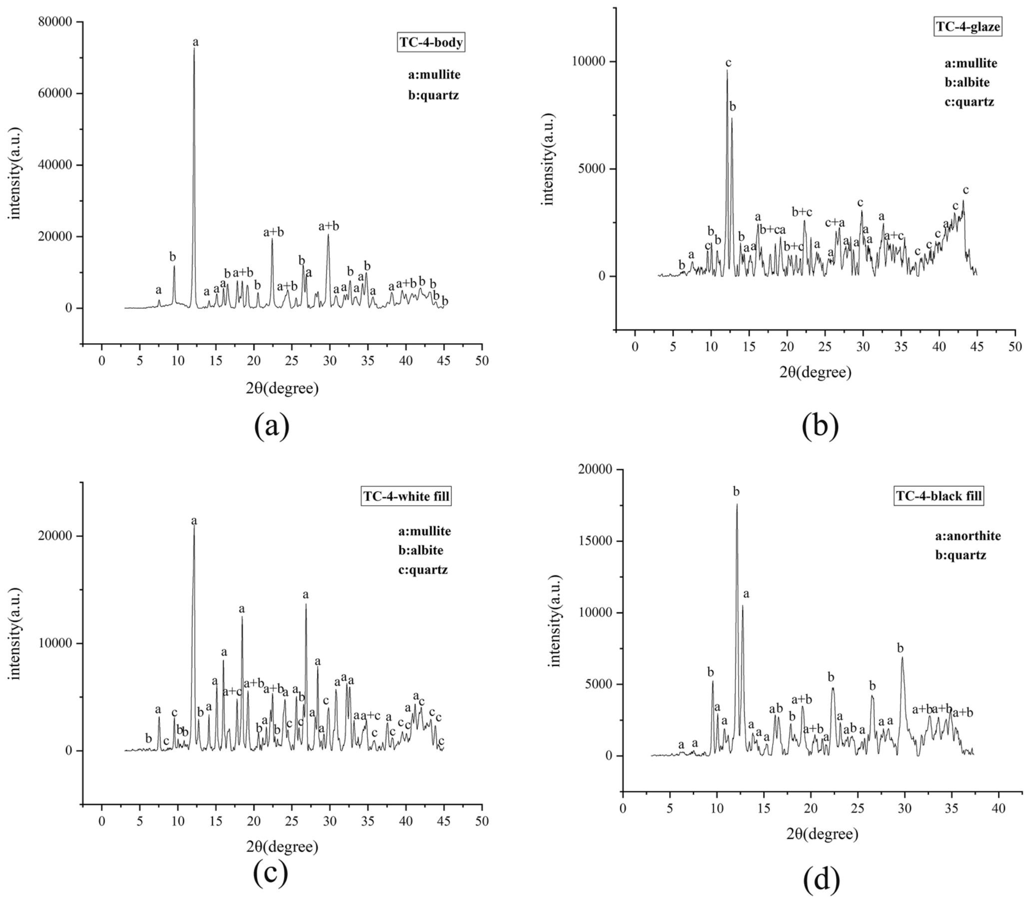


Fig. 4 XRD spectra of Sample TC-4

of 0.09–4.24%. The SEM and XRD results show that the white fills are fired in a single firing under a high temperature. The main component in the XRD image of Sample TC-4 is mullite (Fig. 4c); combined with the SEM data, one can find that the white fill is consistent with the compositional characteristics of kaolin clay, which are high aluminum, low flux, and low iron [24].

In TC-4 and TC-6, the Al_2O_3 contents of the black fills are 19.93% and 24.97%, and the SiO_2 contents are 67.55% and 55.24%; the Al_2O_3- SiO_2 contents recall those of the bodies of the two samples. The MnO contents of the two samples are 0.82% and 2.10%, and the Fe_2O_3 contents are 3.08% and 6.22%. It is worth noting that the white and black fills of TC-4 have similar iron and manganese contents; the reason for the difference in color is that the major constituent of the white fills is kaolinite-dominant, whereas the black fills is mainly comprised of the color-emitting element (Fe element). Combining the SEM and XRD results, one can see that the black fills, like the white fills, are fired in a single firing under a high temperature, and the main components in the XRD images are quartz (Fig. 4d). From this one may conclude that, the black fill is made of quartz with high Fe content or a compound of quartz and raw materials with high Fe content [25].

The Koryŏ celadon was produced mainly in the western coast of the Korean Peninsula, whose latitudinal spectrum correspond to the provinces of Shandong, Henan, Hebei, Shanxi, and Shaanxi, where kaolinite-dominant is abundantly available, in northern China. In general, porcelain wares produced at kilns in northern China were made of the kaolinite-dominant, but the Koryŏ celadon wares were made of low aluminum and high silica porcelain stone, which resonates with the celadon wares of southern China [26]. The underlying reason for this discrepancy lies in the geomorphic formation, where the igneous rocks of southern China extend underneath the East Sea and the Yellow Sea and resurface in Southern Korea, constituting a single tectonic plate [27]. However, kaolinite is also available in waxstone deposits in the Jeolla-nam-do area and scattered in other regions. kaolinite from Gyeongsang-nam-do has been the main raw material for ceramics in Gyeonggi-do, Jeolla-nam-do, and Gyeongsang-buk-do regions [28].

Provenances of the six samples

The authors used energy dispersive X-ray fluorescence spectrometry to analyze the composition of the major elements of the bodies and glazes of the six samples. This instrument, like SEM–EDS, is an energy spectrometry, but it entails different analytical conditions and slightly different data. Because ceramics do not fully retain the original chemical compositions after the production and firing processes, the use of ED-XRF is to obtain a more balanced content of each oxide in the body and glaze of a sample.

Compositional analysis of the bodies for provenance

The authors tested the 10 oxides of Na_2O, MgO, Al_2O_3, SiO_2, P_2O_5, K_2O, CaO, TiO_2, MnO, Fe_2O_3 of the six samples (Table 3). In order to study the provenance of these samples, the authors collected the data of inlay celadon from production sites in Southern Korea and consumption sites in China. Altogether they gleaned the compositional data of 58 samples from 11 kilns, including Yonggunni (late tenth–eleventh centuries), Samhŭngni (late eleventh–twelfth centuries), and Sadangnin (thirteenth–fourteenth centuries) in Kangjin-gun, Chinsanni (eleventh-twelfth centuries) in Haenam-gun, and Undaeri Kiln in Goheung-gun [14], and the data of 20 Koryŏ celadons from the Palace Precinct of the Southern Song dynasty in Hangzhou. It is worth noting that the above data were acquired with the same instrument and working conditions as those of the authors, and appropriate for this study [29].

The K_2O and TiO_2 contents of the samples in Table 3 appear to be somewhat lower than their counterparts in Table 2, whereas the contents of SiO_2 in Table 3 are

Table 3 Major oxides of the bodies (wt%)

Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3
TC-1	0.92	0.43	18.80	72.44	0.00	3.24	0.79	0.54	0.03	2.82
TC-2	0.88	0.97	20.57	69.63	0.00	3.15	1.64	0.57	0.05	2.54
TC-3	0.96	0.45	17.25	74.34	0.00	2.63	0.66	0.70	0.05	2.95
TC-4	0.98	0.46	16.58	75.51	0.00	2.99	0.53	0.67	0.02	2.24
TC-5	0.96	1.59	16.42	75.13	0.00	2.76	0.48	0.59	0.02	2.05
TC-6	0.96	0.45	17.79	74.29	0.00	3.13	0.41	0.63	0.03	2.31
Ave	0.94	0.73	17.90	73.56	0.00	2.98	0.75	0.63	0.03	2.49
1std	0.03	0.43	1.43	2.00	0.00	0.22	0.42	0.06	0.01	0.32

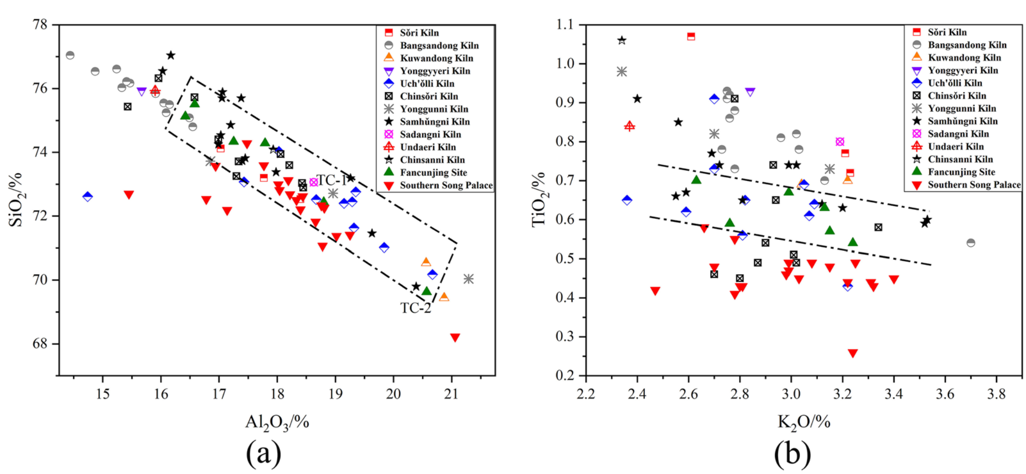


Fig. 5 Binary scatter plot of major oxides of the bodies

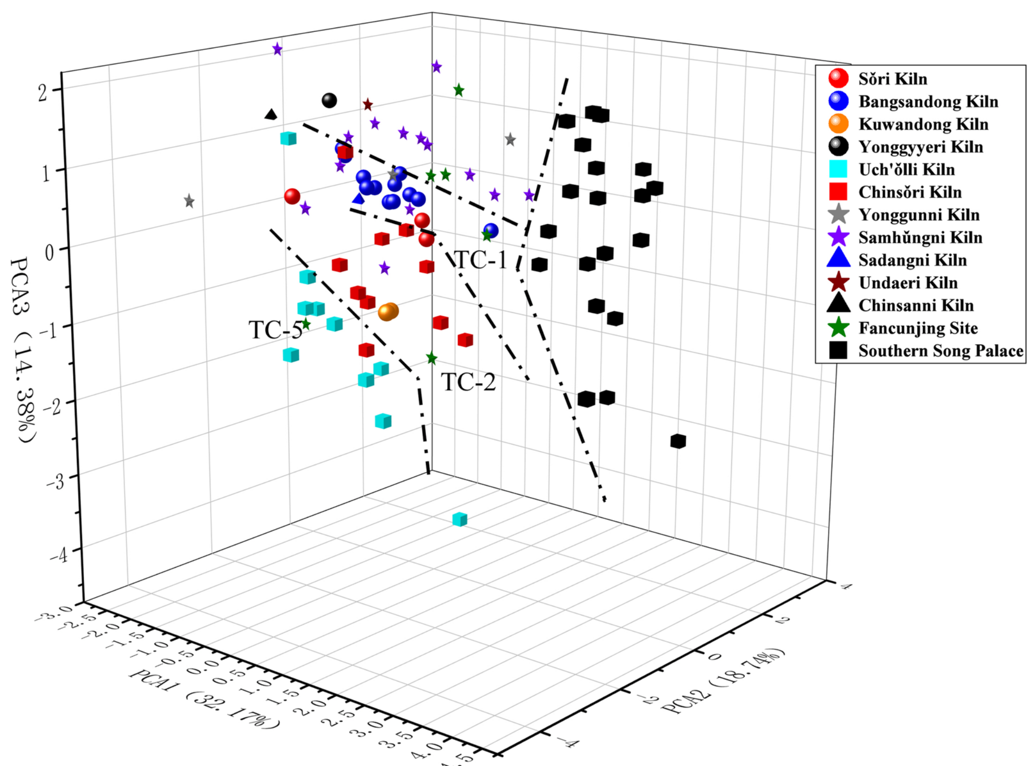


Fig. 6 Principal component analysis of major oxides of the bodies

higher than their counterparts in Table 2. In addition, SEM is not as sensitive to the MnO content as ED-XRF.

The authors plotted the compositional data of the bodies of the six samples with those of the eleven kilns in Southern Korea. The Al_2O_3- SiO_2 contents of the six samples overlap mostly with those of the samples from the Samhŭngni Kiln in Kangjin-gun, the Bangsandong Kiln in the City of Siheung, the Uch'ŏlli and Chinsŏri Kilns in Buan-gun (Fig. 5a); the K_2O-TiO_2 contents of these samples likewise overlap with those of the samples from Samhŭngni, Uch'ŏlli, and Chinsŏri (Fig. 5b).

To further elucidate the provenance of the six samples, the authors conducted the principal component analysis of the compositional data. As shown in Fig. 6, they selected 9 major oxides of the data and extracted three principal component factors. The contribution rate of the three principal components is up to 65.29% [30]. It appears that the three samples TC-3, -4, -6 from the Fancunjing site overlap with the Samhŭngni Kiln in Kangjin-gun; Sample TC-1 concurs with one sample from the Bangsandong Kiln in the City of Siheung; Sample TC-2 clusters with two samples from

Table 4 Major oxides of the glazes (wt%)

Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3
TC-1	0.85	2.22	13.79	61.28	0.00	3.12	16.51	0.19	0.32	1.72
TC-2	0.88	2.48	13.90	64.48	0.00	3.63	12.28	0.24	0.55	1.56
TC-3	0.87	1.93	13.74	64.11	0.00	4.14	12.52	0.21	0.59	1.89
TC-4	0.90	1.52	14.24	58.63	0.00	3.27	19.62	0.13	0.27	1.42
TC-5	0.94	0.90	11.35	67.76	0.00	4.90	12.59	0.13	0.44	1.00
TC-6	0.91	1.76	12.77	66.46	0.00	4.02	12.00	0.19	0.42	1.46
Ave	0.85	2.22	13.79	61.28	0.00	3.12	16.51	0.19	0.32	1.72
1std	0.03	0.51	0.98	3.07	0.00	0.60	2.85	0.04	0.11	0.28

the Chinsŏri Kiln in Buan-gun; Sample TC-5 falls within the group of samples from the Uch'ŏlli Kiln in Buan-gun. In combination with the Al_2O_3- SiO_2 contents and the K_2O-TiO_2 contents in Fig. 4, the three samples TC-3, -4, -6 from the Fancunjing site are probably produced at the Samhŭngni Kiln in Kangjin-gun, whereas the other three are probably produced at the Bangsandong Kiln in the City of Siheung, the Chinsŏri and Uch'ŏlli Kilns in Buan-gun.

Compositional analysis of the glazes for provenance

The authors tested the 10 oxides of Na_2O, MgO, Al_2O_3, SiO_2, P_2O_5, K_2O, CaO, TiO_2, MnO, Fe_2O_3 of the glazes of the six samples, the results of which are given in Table 4.

The MgO and MnO contents in the glazes of the six samples are higher in Table 4 than their counterparts in Table 2, whereas the Al_2O_3 content are lower, which justifies the use of the ED-XRF data for the provenance study.

As shown in Table 4, the glazes of the six samples are made from a mixture of porcelain stone and flux. The CaO contents fluctuate from 12.00% to 19.62%; the MgO and K_2O contents occur within the range of 2.22% and 3.12%; the Fe_2O_3 contents vibrate around 1.72%. The TiO_2 contents are less than 1.00%. The chemical compositions indicate that the glazes of these samples are of the calcium type. Since they all contain a certain amount of Fe_2O_3 and TiO_2, the glazes exhibit colors that range from brownish green to grayish green in response to firing atmosphere. In combination with Table 2, P_2O_5 is nearly absent in the glazes, which suggests that no plant ash be added into the mixtures. In order to enhance the inlay motifs, ancient potters found it indispensable to reduce

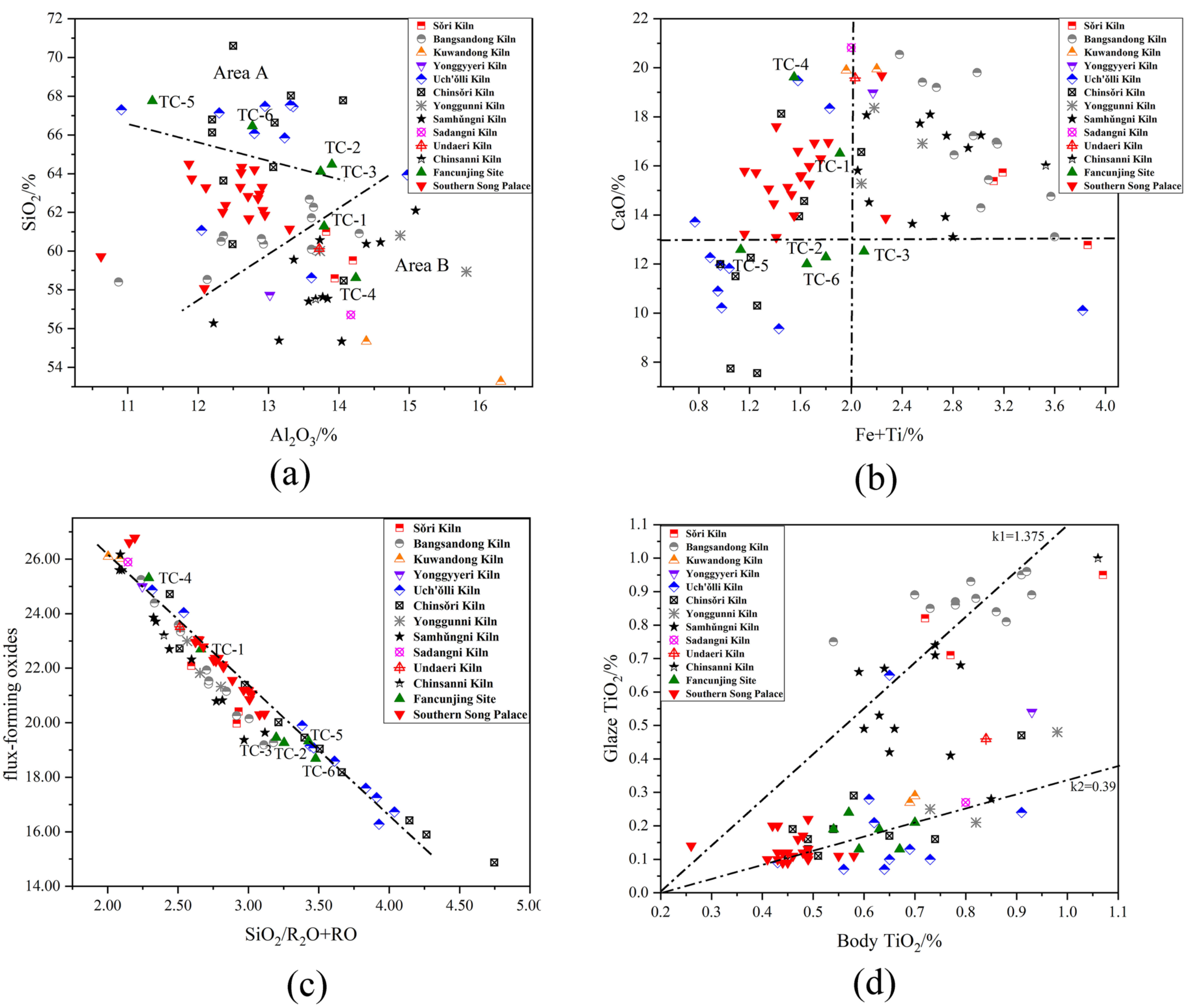


Fig. 7 Binary scatter plot of major oxides of the glazes

the amount of P_2O_5 that produces bubbles. The contents of MnO in the samples, occurring within the range of 0.27–0.59%, give the glaze of Koryŏ celadon more grayish tones.

As in the case of the bodies, the authors analyzed the compositional data of the glazes of the samples from the Fancunjing site, the kilns in Southern Korea, and the Palace Precinct of the Southern Song dynasty in Hangzhou. The Al_2O_3- SiO_2 contents divide the six samples into Area A and Area B. The four samples in Area A, which are high in silicon and low in aluminum, cluster with samples from the Uch'ŏlli and Chinsŏri Kilns; the two samples in Area B, low in silicon and high in aluminum, concur with the samples from the Samhŭngni and Bangsandong Kilns (Fig. 7a). Previous studies have demonstrated that the Fe_2O_3 and TiO_2 contents affect the colors of the glazes of the Koryŏ celadon wares [31]. The Fe_2O_3 and TiO_2 contents of the six samples from Fancunjing fall below 2.00%; in combination with the CaO content, the six samples from Fancunjing agree with samples from the Uch'ŏlli and Chinsŏri Kilns (Fig. 7b). When the celadon ware is fired at a high temperature and cooled rapidly, the high lime component of the glaze produces a transparent glaze that is ideal for displaying the underglaze inlay motifs. At the Samhŭngni and the Uch'ŏlli Kilns, the CaO contents of the lime glazes reach up to 20.00% or more [14]. However, the occurrence of the high and low CaO contents among the six samples is likely derived from their production kilns.

Figure 7c shows that the A silica/flux ratio comparison and flux-forming oxides of Koryŏ inlaid celadon from each site are negatively correlated, with four samples, TC-2, TC-3, TC-5, and TC-6 from the Fancunjing site, clustering with the Uch'ŏlli kiln site. The type of clay used with the flux for the glaze is reflected in the TiO_2 content of the bodies (Fig. 7d). The samples from the Bangsandong and Samhŭngni kilns lie on a slope of 1.375, indicating that the TiO_2 contents in the glazes are higher than those in the bodies. The six samples from Fancunjing, samples from the Palace Precinct of the Southern Song dynasty in Hangzhou, and those from the Uch'ŏlli and Chinsŏri kilns in Buan-gun are spread along a slope of 0.39, implying much less TiO_2 contents in the glazes than in the bodies. One can assume that celadon glazes from these areas are produced by mixing low TiO_2 clays with fluxes.

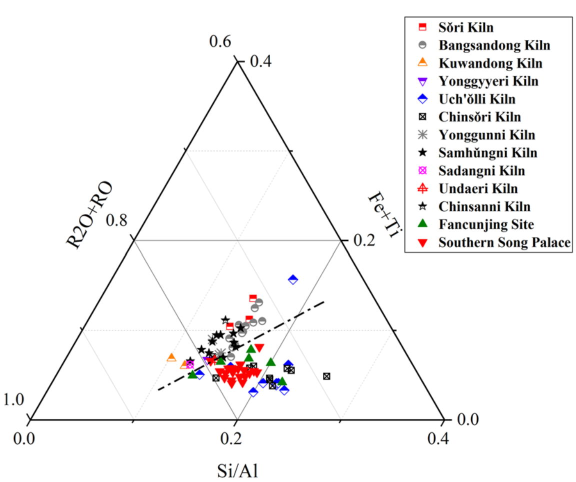


Fig. 8 Ternary diagrams of $R_2O + RO$, Si/Al, and Fe + Ti of the samples

The authors made a ternary diagrams of the fluxes, colorants ($Fe_2O_3 + TiO_2$), and silica-aluminum ratios of the samples (Fig. 8). The presence of alkaline and/or alkaline-earth oxides, such as K_2O, Na_2O and CaO, gives indications on the fusibility of the material, the contents of SiO_2 and Al_2O_3on the refractory characteristics of the paste, while the Fe_2O_3 and TiO_2 percentages determine the colouring of the paste after firing [32]. It appears that the six samples from Fancunjing cluster with those from the Palace Precinct of the Southern Song dynasty, and those from the Uch'ŏlli and Chinsŏri kilns, denoting that the glazes of the samples are made with the same recipe with those of the samples from Uch'ŏlli and Chinsŏri.

In summary, the chemical compositions of the bodies of the six samples indicate that the three samples of TC-3, TC-4, and TC-6 are probably produced at the Samhŭngni Kiln in Kangjin-gun. The glazes, however, are not identified with the Samhŭngni kiln, but with the samples from the Uch'ŏlli and Chinsŏri kilns in Buan-gun. The chemical compositions of the bodies show that the two samples of TC-2 and TC-5 are from the Chinsŏri and Uch'ŏlli kilns; those of the glazes reveal that they are produced with the same recipe as those from the Chinsŏri and Uch'ŏlli kilns. The composition of the body of Sample TC-1 concurs with that of the samples from the Bangsandong Kiln, but that of the glaze finds no comparable sample. The reason why the bodies and glazes of the samples do not agree is probably rooted in the complex processes of the Koryŏ inlay celadon.

Korean scholars believe that the Koryŏ state oversaw the entire sphere of ceramic production at the officially run kilns, including the procurement of high-quality clay, the hiring of skilled potters, and the process of manufacturing. It is possible that raw materials and potters were widely exchanged upon the command of government. The Uch'ŏlli Kiln in Buan-gun was established by workers from Kangjin-gun during the first half of the twelfth century. From the beginning, the celadon wares produced at this kiln are almost identical in form and decoration to those of the Kangjin kilns [33]. Both the Uch'ŏlli and Samhŭngni Kilns supplied high-quality celadon wares to the ruling class of Koryŏ, including the royal family and officials, for both practical and decorative uses [34]. One can also see that the celadon wares were deliberately designed and manufactured to represent the authority of the ruling class. The celadon wares were evidently exported to China and Japan. The Koryŏ ceramics found in China during the Yuan dynasty, however, are mostly inlay celadon and fashion-shaped celadon, and different from the ones discovered at the Koryŏ kilns, implying that they were manufactured particularly for the Chinese clientele.

Conclusion

As described above, the authors carried out SEM–EDS, XRD and ED-XRF analyses of the six samples from the Taicang Port at the Fancunjing site to determine their inlay technique, raw materials, and provenance. It appears that the inlay is rendered in pre-carved lines or directly on the surface of these samples. The bodies are made of porcelain stone, the glazes are of porcelain stone and calcium-rich flux. The white fill is a kaolinite-dominant, whereas the black fill is made of quartz with high Fe content or a compound of quartz and raw materials with high Fe content.

The compositional data of the bodies show that the three samples of TC-3, TC-4, and TC-6 are produced at the Samhŭngni Kiln in Kangjin-gun. The raw material used for the body is consistent with Koryŏ celadon of this kiln. The composition of sample TC-1 overlaps with that of the sample from the Bangsandong Kiln in the City of Siheung. Sample TC-2 is linked with the Chinsŏri Kiln in Buan-gun, whereas Sample TC-5 can be attributed to the Uch'ŏlli Kiln in Buan-gun. The analysis of the glazes of these samples reveals that they are produced with a recipe similar to those of Uch'ŏlli and Chinsŏri kilns in Buan-gun, presumably as a result of the supply of high-quality raw materials and the exchange of kiln workers.

Foreign policy and trade between the Koryŏ dynasty and the Southern Song and Yuan dynasties had a great bearing on the exchange of cultural artifacts. The Koryŏ inlay celadon found at the Fancunjing site appears to be trade or tribute items delivered from the Koryŏ dynasty to the Yuan dynasty. The compositional data of the bodies of the samples suggests that these samples are from different kiln sites in the Koryŏ dynasty. As the Bangsandong, Samhŭngni, Chinsŏri, and Uch'ŏlli Kiln are of various dates, the samples from the Fancunjing site could not have been imported as a single shipment, but rather as multiple shipments.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-023-01089-x.

Additional file 1: Table S1. Measured and standard values of Corning-D reference glass and soil specimen (GSS5) sintered at 1200°C (Note: GSS5 standard values are calculated from the original standard values minus the values of loss on ignition).

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Author contributions

LZ designed research; DC performed research; ZZ contributed the samples and the excavation information; DC, XL analyzed data; DC wrote the paper. The authors declare no competing interest. To whom correspondence may be addressed. Email: zhlr@nju.edu.cn.

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Availability of data and materials

We would like to state that all the data that supports the findings of this study are included within the manuscript and supplementary files; the data cited from the other sources can be found in the referenced articles.

Declarations

Consent for publication

All authors approved the final manuscript and the submiss to this journal.

Competing interests

The authors declare that they have no competing interests.

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