Technical Studies and Replication of Guan Ware, an Ancient Chinese Ceramic

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Introduction

When North China was invaded in 1127, the emperor of the Song dynasty moved the capital to Lin'an (now called Hangzhou) in Zhejiang Province southeast of Shanghai. He established the Southern Song dynasty (1127–1279 A.D.), known as a period of cultural flowering and stability in Chinese history. Several years later, official kilns were built by court officials to meet the need for the porcelains required for use at the Southern Song palace. A new style of porcelain ware, known as Southern Song Guan ware ("Guan" meaning "imperial"), was produced that differs in appearance (Figure 1) from any of the ceramic ware made for the Northern Song dynasty court. These new kilns collectively are called the Southern Song Guan kilns. Compared with what we know of the long tradition and technology of manufacturing celadons (pottery having a pale green glaze) in the north and the south of China, the Guan kilns created celadons distinguished in having a translucent, crackled glaze with a wide variation of jade-like colors, a thin body of 1–5 mm, a thick glaze that is often thicker than the thinnest bodies, and special features called "purple mouth" and "iron foot." Because the quality of the celadons was unprecedentedly high, scholars for the last 700 years consistently have classified Southern Song Guan ware as one of the "five classic wares" of the Song dynasty.

Literary References

According to the book *Tan Zhai Bi Heng*, written by Ye Zhi, a writer of the Southern Song dynasty, that has been cited frequently by other authors but of which we no longer have an original copy, the Southern Song Guan kilns were established in two places in Hangzhou. Nei Yao (the imperial kiln) was first established at Xiuneisi (the Bureau of the Imperial Household) near Wansongling (the Forest of 10,000 Pines) at the foot of Fenghuangshan (Phoenix Hill), and then somewhat later, another new kiln was set up in the foothills, Wuguishan, below the "suburban altar" where the emperor made offerings to begin each new planting season. These kilns became known as the Xiuneisi Guan kiln and the Jiaotanxia ("altar") Guan kiln. The woodblock print of an ancient map shown in Figure 2 shows the relationship among these various sites.

Archaeological Excavations

Although sherds were collected at the Jiaotanxia Guan kiln in the 1930s, a scientific excavation was not carried out until the early 1980s.[1] A scientific and technological study followed soon after,[2] and now a museum has opened on the site that allows visitors access to a 40.8-m-long "dragon kiln" and the workshop area. The dragon kiln found at this site is the largest ever found. It is a hill-climbing kiln that is fired in stages from the lower portion to the upper end through fireholes or fireboxes placed intermittently along one side. Dragon kilns are similar to modern tunnel kilns, in that the incoming air from below is preheated as it passes over the already fired lower region before it reaches the region of the kiln that is being stoked. The ware above is preheated slowly by the flow of gases up the tunnel. This type of kiln fires for several days and maintains peak temperature for a considerable length of time such that the microstructures of the ware are well developed, and nucleation and crystal growth can occur in glazes and at glaze–body interfaces.

Although an intensive surface survey has uncovered some sherds at Wansongling, no kilns have been found there. However, a kiln site was discovered in 1996 about 2.5 km away from the Jiaotanxia Guan kiln site at Laohudong (Tiger Cave), a relatively inaccessible site in a small, steep valley to the south of Wansongling (see Figure 2). Since 1998, a 15-m-long dragon kiln and three bisque-firing (first-firing) kilns have been excavated; a large enclosure wall has also been found. In total, the excavations have covered about 800 m^2. A workshop area to the east of the kiln contained large vats of raw glaze. A large quantity of glazed sherds, bisque-fired sherds, and kiln furniture, such as setters (supports) and saggars (coarse ceramic containers for protection of the ware during firing and cooling), have been excavated in the Southern Song stratum. In addition, a later Yuan dynasty (1271–1368 A.D.) stratum that overlies the Southern Song stra-

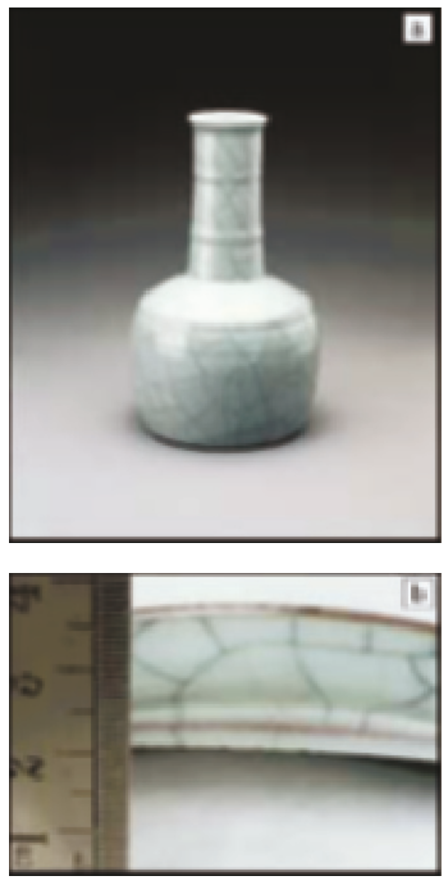

Figure 1. (a) Example of Guan ware (height: 25 cm). (b) Cross section of Guan ware sherd showing thin gray body, thick green glaze, and two-color crackle pattern called "iron wire and golden thread" (From Reference 5). Size marker is in centimeters.

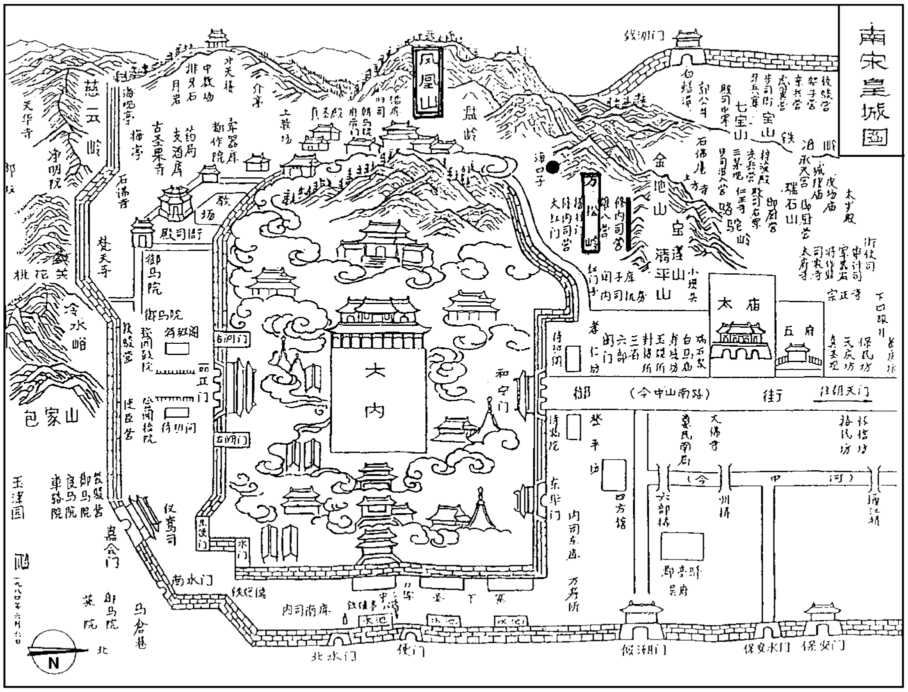

Figure 2. Woodblock print of ancient map showing Lin'an Imperial Palace (near center) and the Southern Song Guan kilns. The Jiaotanxia Guan kiln site was located at Wuguishan below the "suburban altar" (just off the map, on the left); the Laohudong (Tiger Cave) kiln site excavation is indicated by the solid circle at upper right. Fenghuangshan, or Phoenix Hill (double box), is above the palace site. Xiuneisi, or the Bureau of the Imperial Household, is indicated by the thick vertical line. Wansongling, or the Forest of 10,000 Pines (box), is between Laohudong and Xiuneisi.

tum revealed large quantities of kiln furniture and sherds with a slightly different visual appearance. The excavators conjectured that the sherds from the Southern Song stratum in the Laohudong kiln site are Xiuneisi Guan ware.[3]

Research Plan

We studied the sherds collected on the surface at Wansongling and confirmed that they were fired in Hangzhou, owing to the similarity in the chemical compositions of their bodies and glazes, their microstructures, and their firing practices, but we found that many were not fired in the same kiln as the sherds of Jiaotanxia Guan ware.[4] Rather, we will show that these sherds from Wansongling were fired in the Laohudong kiln. On the basis of this research, and in order to better understand the chemical and technological breakthroughs that characterize the visual appearance of Southern Song Guan ware, we scientifically studied and replicated this ware.[5]

Experimental Results

The colors of the bodies of the excavated and collected sherds vary from dark gray to dark brown. Just like the color variations of real jade, celadon glazes vary in color from gray-green to fresh pale green and occasionally warm white. They are generally somewhat opaque to translucent and have a crackle pattern of T-shaped craze lines due to differential contraction on cooling of the body and glaze. Owing to the differences in the shapes of the vessels, the thicknesses of the bodies may vary from one to several millimeters. The glazes vary from 0.5 mm to 1–2 mm thick. Some glazes are thus thicker than the bodies that they decorate (Figure 1b). The most famous Southern Song Guan ware has a thin body and a thick glaze, and shows a characteristic change in glaze color at the rim, called "purple mouth," and a re-oxidized reddish color on the exposed clay body at the foot-rim, called "iron foot."

Chemical compositions of bodies and glazes are shown in Table I for Guan ware sherds collected from Jiaotanxia, from the Laohudong kiln excavated in the Song and Yuan strata, and from the Wansongling surface collection. In addition, compositions from a sherd of the so-called "handed-down" Ge (older brother's) ware that was supplied by the Palace Museum in Beijing is included for comparison with the Yuan-period Guan ware from Laohudong.[6] These compositions are plotted in Figures 3 and 4, which show the body and glaze variations, respectively, in factor-loading diagrams.

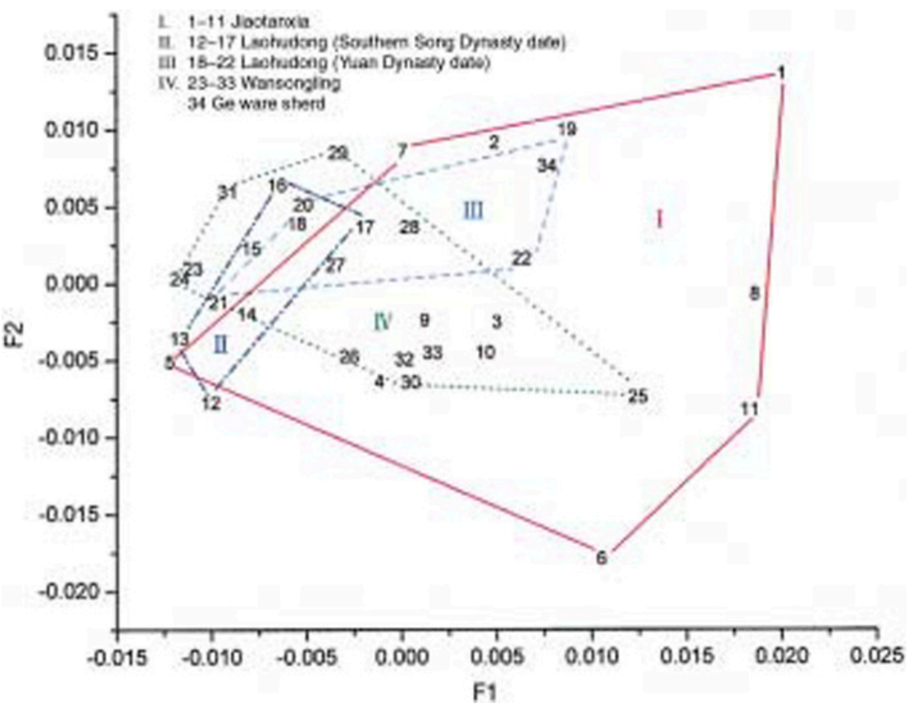

Figure 3. Factor-loading diagram that differentiates the chemical compositions of the bodies of sherds found at different kiln sites.

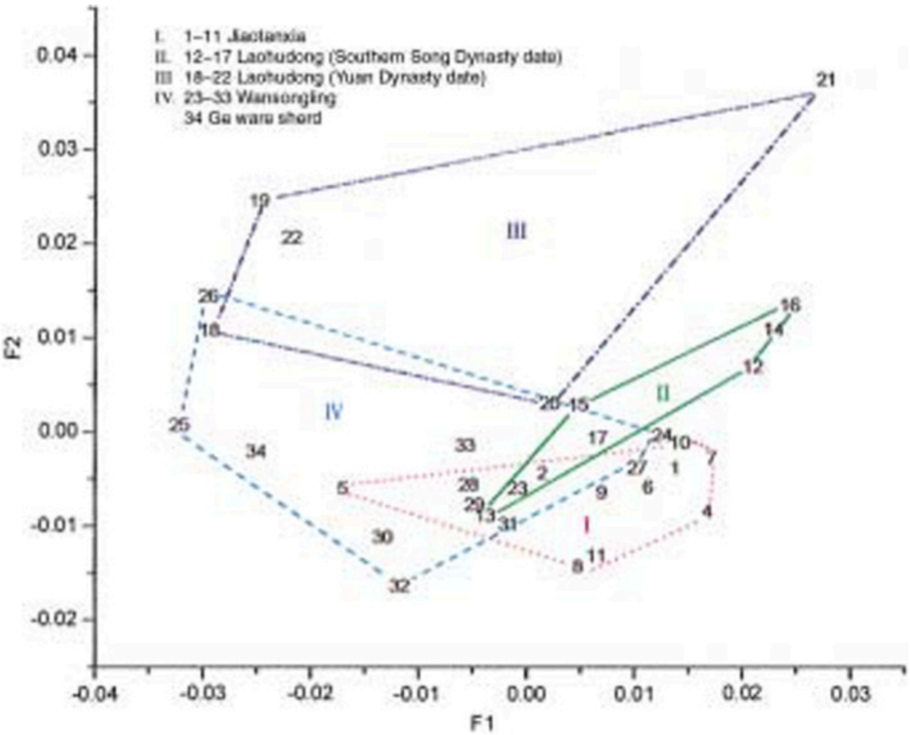

Figure 4. Factor-loading diagram that differentiates the chemical compositions of the glazes found on sherds at different kiln sites.

The microstructures of the bodies and glazes were analyzed by polarizing light microscopy. The microstructures of the bodies for all Southern Song Guan ware varied only slightly from one sample to another. The major phase present was residual quartz of different sizes, with a small amount of mullite, a residue of mica, some iron oxide, and some glassy phase. The microstructures of the glazes were more complex and fell into two classes. One group contained more anorthite crystals and fewer small bubbles in a glassy matrix; the other one contained more small bubbles and fewer anorthite crystals. These differences are probably due to the variations in firing time and temperature that are common in the large hill-climbing dragon kilns as they are sequentially fired.

The firing technology and properties of these ceramics show the most variation from sample to sample. The optimum firing temperature is between 1200°C and 1270°C, based on a test of refiring an underfired sample of Jiaotanxia Guan ware, and the optimum firing atmosphere was found to be a heavily reducing one.[2] Based on refiring an underfired sherd from Wansongling, the optimum firing temperature was between 1200°C and 1240°C, but an even heavier reducing atmosphere was required than that for the Jiaotanxia sample.[4] For the Jiaotanxia Guan ware bodies, the water absorption for most of the sherds was 0.40–1.5 wt%, except for some underfired sherds that had higher water absorption. The range of water absorption for correctly fired sherds from Laohudong and Wansongling was 0.19–1.99%.[7] These values are larger than for modern vitreous porcelains and are more similar to those of modern stoneware, hotel china, and sanitary ware.

Replication of Southern Song Guan Ware

According to the results just presented, the chemical compositions and microstructures of the bodies and glazes of Jiaotanxia Guan ware and their firing temperatures can be analyzed, but many details of the firing process are poorly understood. The reason is that there are no records of craft processes among the available historical materials. Therefore, a complete picture of the firing process can only be acquired through replication. To do this, a small-scale workshop, called Keyao (institute kiln), was set up at the Shanghai Institute of Ceramics, where modern science and technology could be combined with traditional manufacturing techniques. Commercial materials were compounded, hand-thrown, and fired in a small gas-burning furnace. Shapes included bowls, dishes, zun (decorative jars for display), and incense burners (Figure 5). After shaping the body, bisque-firing it, dipping it in the glaze, and firing it, variations in the microstructure, physical properties, color, and crackle pattern were observed.

Next we discuss the complex relationship between the manufacturing tech-

Figure 5. Replicas of Guan celadon ceramics from the Keyao (institute kiln) workshop.

Table I: Chemical Composition of Bodies and Glazes of Guan Ware Sherds in wt%.

Dynasty	No.	Sample	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	MnO	P_2O_5
Southern Song Jiaotanxia	1	WJ10B	61.27	28.81	4.12	0.67	0.21	0.62	4.16	0.19	—	0.08
Guan Ware		WJ10G	65.4	14.63	0.69	0.08	13.45	0.66	3.99	0.2	—	0.4
	2	WJ11B	64.63	26.45	2.75	1.3	0.17	0.25	3.68	0.73	—	0.1
		WJ11G	66.97	14.53	0.97	—	11.93	0.58	4.24	0.74	—	0.26
	3	WJ13B	66.56	24.24	2.63	1.08	0.32	0.36	3.71	0.28	—	0.09
		—	—	—	—	—	—	—	—	—	—	—
	4	WJ16B	68.72	23.59	2.07	1.1	0.6	0.34	3.12	0.3	—	0.13
		WJ16G	65.89	15.17	0.82	—	13.56	0.64	3.38	0.22	—	—
	5	WJ17B	69.58	24.44	1.88	—	0.11	0.14	2.88	0.39	—	—
		WJ17G	68.28	14.57	1.3	—	8.89	0.81	4.55	1.3	—	—
	6	WJ18B	69.79	20.59	3.09	0.73	0.32	0.7	3.75	0.39	—	0.08
		WJ18G	65.15	16.1	0.96	—	12.5	0.75	3.46	0.28	—	0.28
	7	NSGY1B	65.05	26.74	2.81	1.47	0.33	0.14	3.04	0.24	—	—
		NSGY1G	65.38	13.66	0.79	0.25	14.58	0.65	3.94	0.38	—	—
	8	NSGY2B	65.29	23.56	4.22	2.11	0.2	0.35	4.22	0.24	—	0.09
		NSGY2G	65.71	16.67	0.76	—	10.9	0.59	3.87	0.3	0.14	—
	9	NSGY3B	67.04	23.43	1.92	2.17	0.15	0.36	3.63	0.33	—	0.07
		NSGY3G	67.36	14.46	0.86	—	11.71	0.65	3.48	0.26	—	0.67
	10	WGS1B	67.45	23.42	3	1.25	0.32	0.17	3.69	0.26	—	—
		WGS1G	64.76	14.51	0.76	—	13.94	0.74	4.55	0.2	—	0.31
	11	WGSMB	66.61	22.67	3.86	1.33	0.08	0.76	4.12	0.18	—	—
		WGSMG	67.13	14.57	0.93	—	11.57	0.5	4.47	0.19	—	—
Laohudong Ware of	12	98LYH3:1B	70.11	22.86	2.55	1.19	0.14	0.25	2.11	0.18	0.016	0.28
Southern Song Stratum		98LYH3:1G	63.05	14.33	0.93	0.1	15.65	0.89	4.07	0.29	0.31	0.39
	13	98LYH3:2B	69.42	23.85	2.41	1.28	0.13	0.24	1.93	0.23	0.016	0.29
		98LYH3:2G	67.36	15.19	1.11	0.091	9.64	0.72	4.25	0.36	0.3	0.56
	14	98LYH4:2B	68.72	24.41	2.33	1.29	0.12	0.25	2.5	0.22	0.021	0.27
		98LYH4:2G	62.57	13.87	1.01	0.12	16.33	0.95	3.6	0.47	0.31	0.4
	15	98LYH1:3B	67.51	25.09	2.75	1.28	0.15	0.21	2.11	0.3	0.019	0.29
		98LYH1:3G	64.52	15.64	1.16	0.12	12.17	1.1	4.42	0.4	0.21	0.52
	16	98LYH1:2B	66.15	25.81	2.92	1.3	0.1	0.19	2.14	0.39	0.017	0.29
		98LYH1:2G	61.87	14.65	1.01	0.11	16.81	1.09	3.72	0.45	0.23	0.4
	17	98LYH1:1B	66.3	25.59	2.54	1.1	0.14	0.36	2.86	0.45	0.016	0.3
		98LYH1:1G	66.35	14.49	0.98	0.11	12.28	1.08	3.9	0.39	0.24	0.39

nique and the desired visual and tactile characteristics of first-quality Southern Song Guan ware, such as "purple mouth" and "iron foot," the "iron wire and golden thread" crackle pattern, the fresh pale green color, thin body and thick glaze, and strong jade-like appearance.

The replicas have residual quartz particles, small bubbles, and a high density of microcrystals in the glaze (Figure 6) and have microstructures similar to those of the Jiaotanxia Guan ware. In order to identify the microcrystals, electron-probe microanalyzer (EPMA) compositional data were compared with backscattered-electron images that were also analyzed by energy-dispersive spectrometry (EDS). The microcrystals were mainly the anorthite phase (Figures 7a and 7b), as confirmed by a chemical composition of 47.2 wt% SiO_2, 15.7 wt% CaO, and 36.9 wt% Al_2O_3. The microcrystals and small bubbles cause the jade-like appearance of the glaze because of their strong scattering effect. The jade-like appearance of the Jiaotanxia Guan ware is also mainly dependent on these anorthite crystals formed during firing. The high calcium oxide content of the glaze is one factor in their formation, but if the firing temperature is too high, and the anorthite crystals are remelted, transparency of the glaze increases, and the jade-like appearance is lost. Therefore, we have determined that the firing temperature cannot exceed 1240°C in order to produce first-quality Guan ware.

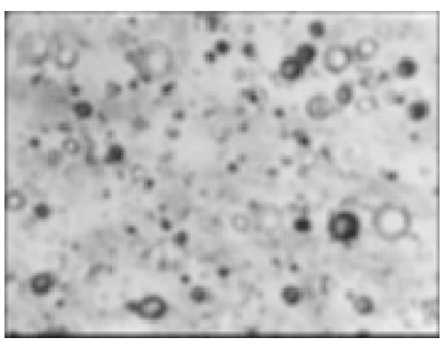

Figure 6. Photomicrograph of Guan glaze showing bubbles and anorthite crystals (74×).

The main factor influencing the crackling is the difference in the coefficients of thermal expansion (CTEs) of the body and glaze after firing. The CTEs measured between 20°C and 500°C for the body and glaze were 5.70×10^{-6} and 6.19×10^{-6}, respectively. The CTE of the glaze, being larger than that of the body, is in accord with the fundamental demand that the

Table I: Chemical Composition of Bodies and Glazes of Guan Ware Sherds (cont'd.).

Dynasty	No.	Sample	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	MnO	P_2O_5
Laohudong Ware of Yuan Stratum	18	98LYT74: ②②B	67.01	25.51	2.91	1.32	0.16	0.21	2.29	0.3	0.018	0.29
		98LYT74: ②②G	65.41	14.41	1.35	0.1	8.55	1.26	6.58	1.63	0.53	0.53
	19	98LYT74:②:1B	64.1	27.16	2.72	1.32	0.25	0.49	3.73	0.62	0.025	0.3
		98LYT74:②:1G	61.42	15.75	1.33	0.09	10	1.74	6.36	1.68	0.52	0.9
	20	98LYT19:②:1B	66.21	25.56	2.46	1.26	0.16	0.22	2.61	0.5	0.019	0.29
		98LYT19:②:1G	65.11	13.56	1.2	0.092	12.81	0.66	5.1	0.77	0.11	0.31
	21	98LYT39:②:2B	68.41	24.33	2.28	1.3	0.13	0.24	2.27	0.3	0.019	0.29
		98LYT39:②:2G	60.25	13.12	1.74	0.3	18.25	2.23	2.75	0.61	0.48	0.98
	22	98LYT57:②:1B	65.28	24.74	3.28	1.24	0.2	0.41	3.22	0.33	0.03	0.3
		98LYT57:②:1G	62.3	14.43	1.01	0.061	10.75	1.42	6.96	1.55	0.41	0.78
Sherds Collected on Wansongling Ground	23	HX11B	68.71	25.02	2.41	1.05	0.069	0.13	2.31	0.42	0.012	0.06
		HX11G	69.11	13.46	0.7	0.11	10.44	1.25	3.97	0.31	0.28	0.43
	24	HX12B	68.54	24.96	2.25	1.13	0.076	0.14	2.32	0.26	0.002	0.022
		HX12G	66.47	14.01	0.56	0.089	13.45	1.21	3.56	0.32	0.24	0.27
	25	HX14B	67.34	21.94	3.94	1.08	0.29	0.37	3.64	0.7	0.024	0.095
		HX14G	71.54	11.26	0.47	0.037	7.22	1.43	4.93	1.64	0.44	0.53
	26	HX15B	68.51	23.14	3.26	0.96	0.12	0.29	2.43	0.47	0.023	0.14
		HX15G	66.42	14.57	0.63	0.047	8.45	1.94	5.55	1.66	0.5	0.75
	27	HX16B	67.01	25.04	2.01	1.15	0.18	0.2	3.4	0.42	0.012	0.28
		HX16G	66.53	14.49	0.82	0.08	12.69	0.82	3.3	0.39	0.19	0.39
	28	HX17B	65.91	25.6	2.63	1.02	0.12	0.43	3.01	0.48	0.014	0.3
		HX17G	68.42	13.11	0.74	0.06	10.73	0.72	5.15	0.62	0.11	0.38
	29	HX18B	65.05	26.54	2.3	1.18	0.14	0.16	3.13	0.48	0.014	0.28
		HX18G	68.21	14.75	0.82	0.07	9.88	0.76	3.77	0.6	0.16	0.6
	30	HX19B	68.21	22.97	2.61	0.97	0.13	0.28	3.49	0.44	0.014	0.25
		HX19G	69.01	13.96	0.83	0.06	8.62	0.66	5.12	0.63	0.12	0.41
	31	HX20B	66.41	26.1	2.53	1.13	0.13	0.2	2.12	0.31	0.012	0.31
		HX20G	67.15	16.68	0.89	0.12	9.8	0.77	3.7	0.34	0.14	0.62
	32	HX21B	67.43	23.47	2.41	0.93	0.11	0.33	3.51	0.36	0.015	0.27
		HX21G	68.97	14.84	1	0.07	7.83	0.47	4.15	0.5	0.06	0.51
	33	HX22B	67.72	23.61	2.89	1.09	0.12	0.35	3.28	0.28	0.016	0.29
		HX22G	67.3	13.58	0.8	0.06	10.69	0.45	5.22	0.52	0.06	1.11
"Handed-Down" Ge Ware, Supplied by Beijing Palace Museum	34	SKO1B	64.33	25.97	3.31	1.27	0.42	0.56	2.68	0.74	—	—
		SKO1G	66.62	16.46	0.78	0.04	8.38	1.01	4.46	1.85	0.24	—

glaze be in tension. However, the amount of crackling and its distribution are influenced by firing temperature, heating rate, cooling rate, atmosphere, and time.

The iron content in the body and glaze is the main factor determining color, if the remaining composition is held constant, but even small variations in firing have a significant effect on color. If a heavy reducing atmosphere is used, then 3.5 wt% Fe_2O_3 produces a black-brown body, and 0.80% Fe_2O_3 makes a fresh green glaze. If the viscosity of the glaze is properly controlled, then the glaze at the rim and ridged decoration is thinner than that on the rest of the body, and the dark body shows through the glaze, giving the effect known as "purple mouth" (Figures 1b and 5). Where the foot rim is unglazed, it turns reddish-brown in the firing, thus forming the characteristic "iron foot."

A crackle in the glaze will appear with normal firing; it forms in the process of cooling, when the sample is taken out of the kiln. The cracks initiate during cooling, but continue to grow later. We believe that the two-color crack pattern is a post-firing treatment—the crackle is stained black when the sample has just been taken

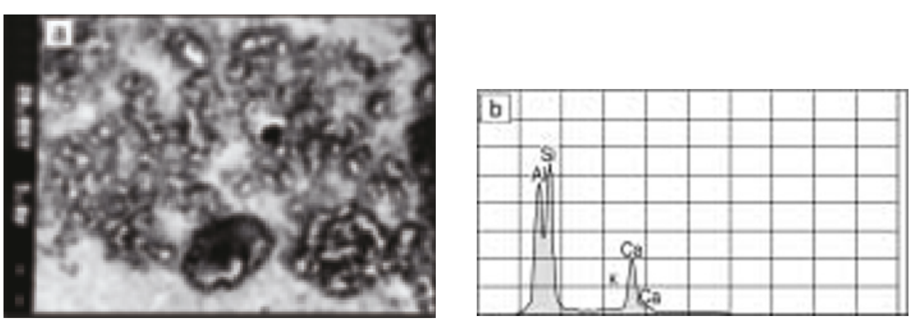

Figure 7. (a) Backscattered compositional image showing anorthite at 1500× and (b) EDS spectrum showing high calcium and aluminum oxide content.

out of the kiln, and then, after a period of time, newly formed cracks are stained ginger, yielding the so-called "iron wire and golden thread" pattern that is one of the distinguishing traits of Guan ware.

Unlike the ancient workshop practices, the two Chinese characters for Keyao (i.e., "institute kiln") were pressed into the bottom of each replica.

Results and Discussion

The excavations at the Laohudong and Jiaotanxia kiln sites indicate that a small amount of an earlier transparent celadon ware, called Yue ware, was produced and fired at these sites during the Northern Song dynasty. This evidence shows that "folk" kilns firing Yue celadon were present prior to Guan ware production, and that technological problems, such as raw-material selection, craft practice, and skill of workers, had been solved. These earlier kilns served to enable the establishment of the Guan kilns and provided some continuity in technology. Later Yuan dynasty products found above the Southern Song layer show that the two kilns also continued production after the fall of the Song dynasty.

At the beginning of Southern Song Guan ware production, the firing technology was apparently most influenced by the northern imperial porcelain production of a purplish blue-green ware from the Ru imperial kilns from the Northern Song dynasty, so it is probable that managers, imperial quality standards, and some know-how came from the north. However, considerable adaptation of both northern and southern styles of technology occurred at the Guan kilns to produce the outstanding Guan product. For instance, Yue ware was a mature technology using the porcelain and reddish-purple clays that abound in the south, as well as the dragon kiln design that only existed in the south. The Guan ware bodies have lower Al_2O_3 and higher Fe_2O_3 contents as compared with Ru ware, and they were fired in a heavier reducing atmosphere and at a lower temperature to produce the characteristic dark-brown body and pale green glaze. Confidence in the newly developed technology is demonstrated by the increase in size and complexity of firing evident in the later 40-m Jiaotanxia kiln.

In Figure 3, we see that the sherds excavated from the Southern Song and Yuan strata and those collected at Wansongling all lie in or near Area I and that most Wansongling sherds were fired in the Laohudong kiln. Moreover, the sherds excavated in the Southern Song and Yuan strata are grouped in two overlapping areas, II and III, respectively. Area II has a higher SiO_2 content than Area III, showing that although the sherds were fired at the same kiln site, the raw materials or recipes have changed over time. The Wansongling sherds are distributed over the larger Area IV, which has both higher and lower SiO_2 contents, but they may include sherds from the Southern Song and Yuan strata, as they were not from a controlled excavation; thus their usefulness in making interpretations is limited. Sherd No. 34 in Figure 3, the Ge ware from the Palace Museum in Beijing, is located in Area III, the Yuan stratum of Laohudong. The similarity of its composition shows that Ge ware may be an imitation of Guan ware, produced at the Laohudong kiln in the Yuan dynasty.

In Figure 4, we see that the Jiaotanxia Guan ware glazes are concentrated in the lower part (Area I) of the diagram. The small size of Area I indicates a small variation in composition. The sherds excavated from the two levels at Laohudong form two disjointed areas (II and III) that are quite dispersed. Area II (Song) is closer to Area I than Area III (Yuan), indicating that Jiaotanxia glazes are closer in composition to the Laohudong Song ones. The CaO content in the Yuan glazes is lower and the K_2O and Na_2O contents are higher. This compositional proximity may indicate a relationship of inheritance or technology transfer with the Jiaotanxia kiln developing after the Southern Song stratum at Laohudong. This conjecture is in accordance with the historical record that the Nei Yao (imperial kiln) was first established at Xiuneisi and then another new kiln was set up at Jiaotanxia. It also supports the inference that the Song stratum of Laohudong is the same at the Xiuneisi Guan ware kiln. The sherds collected at Wansongling again show a wide compositional dispersion in Area IV that limits interpretation beyond showing that their dating may be mixed. The Ge ware sherd, No. 34, is found in the lower-left part of Area IV and is most similar to the Laohudong Yuan dynasty sherds having lower CaO content and higher K_2O and Na_2O contents, reinforcing the conclusion that Ge ware was fired at Laohudong during the Yuan dynasty.

The microstructures of Southern Song Guan ware glazes can be divided into two classes based on the relative amounts of anorthite and bubbles that contribute to the jade-like appearance of the glaze. The Laohudong glazes of the Southern Song period and the Jiaotanxia glazes contain more of the anorthite phase and fewer small bubbles than the Laohudong glazes of the Yuan period, owing to the chemical composition of the glazes. A higher CaO content favors the formation of the anorthite phase. The microstructure of the Ge ware also contains less anorthite and many small bubbles,[6] consistent with its identity as a Laohudong glaze of the Yuan dynasty. The glaze microstructures of the Guan ware replicas are most similar to those of Jiaotanxia Guan ware.

The Southern Song dynasty Guan glazes display the best imitations of a jade-like appearance and are the most highly prized (and costly). They appear to have the most depth and translucency; however, the variations in color from white to green to gray are larger than those of Yuan dynasty ware, in which green predominates. The color, however, is not related to the variation of chemical composition within the limited compositional region we have established. Instead, the color variability is related to differences in firing temperature and atmosphere along the great length of the dragon kilns. In general, the highest-quality, pale green glazes are fired in a heavily reducing atmosphere at a temperature of 1200–1240°C.

Conclusions

For replicating Guan ceramics from the Southern Song stratum at the Laohudong and Jiaotanxia kiln sites, local materials from Hangzhou were selected, and the ware was fired locally. Our analyses support the conclusion that the Southern Song stratum of the Laohudong kiln is probably the Xiuneisi Guan ware described in the *Tan Zhai Bi Heng*, but the final resolution will be made by local archaeologists.

Differences were found in the chemical compositions and microstructures of the bodies and glazes of sherds from the Southern Song stratum and of those from the Yuan stratum at the Laohudong kiln. The major differences are in the glazes. The Laohudong Guan glaze composition from the Southern Song stratum is more similar to that of Jiaotanxia than to Yuan glazes from Laohudong. This suggests that the Jiaotanxia kiln developed out of practices at the Laohudong kiln, an interpretation supported by literary evidence.

The chemical composition and microstructure of the body and glaze of the Ge ware sherd from the Palace Museum in Beijing are most similar to those characteristic of sherds excavated in the Yuan period stratum of the Laohudong site. Therefore, based on our limited sample, we suggest that Ge ware is an imitation of Guan ware that was fired in the Laohudong kiln during the Yuan dynasty. The sherds collected at Wansongling are the products of the Laohudong kiln from both the Southern Song and Yuan periods.

Replicas of Southern Song Guan ware have been made successfully on the basis of the research into the manufacturing technology used. The materials research and the replica manufacture have mutually reinforced our conclusions and results.

Finally, an understanding of the minor differences in the visual appearance of famous ancient ceramics, usually thought to be the exclusive preserve of art historians, curators, and collectors, can be achieved through materials science and engineering.

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