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한국 전통 도자기의 화학 조성에 대한 연구 (I): 고려청자와 고려백자

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A Study of the Chemical Composition of Korean Traditional Ceramics (I): Celadon and Koryŏ Whiteware

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초 록 중국 도자기에 대한 과학적 연구는 화학적 성분분석을 중심으로 18세기부터 구라파에서 지속적으로 이루어졌으며, 중국내에서는 1950년대부터 시작되었다. 반면에 한국도자기의 경우는 1980년대에 미국과 독일에서 연구가 이루어지고 한국내에서 체계적 연구는 1990년대부터 시작되었다. 이와 같은 도자기 연구는 많은 분석 결과들이 축적됨에 따라 여러 도요지들을 서로 비교하고 중국의 분석 결과와도 비교가 가능하게 되었다. 이 논문에서는 고려청자와 고려백자를 생산도요지와 발굴층위 등에 따라 각각 21그룹과 10그룹으로 나누어서, 성분결과들을 비교 관찰하였다. 각 그룹의 태토와 유약의 성분은 일반적으로 3~5편을 분석하고 그들의 분석값을 평균하였다. 비교 결과에서 한국도자기의 태토는 월주요와 경덕진요와 같은 중국 남방에서 사용되고 있는 운모-석영계의 도석으로 만든 것으로 나타나며, 유약도 중국과 유사하게 점토와 나무재, 그리고 석회석 종류의 용융재를 혼합하여 만든 것으로 추정된다. 특히, 석회석은 처음에 태워서 사용하다가 고려말기에 이르러 분말상태로 사용하는 경우가 많아지는 경향을 보인다. 월주요에서 사용한 유약은 몸체를 만든 태토를 섞은 것에 비하여 강진 청자의 유약은 백자를 만들 수 있는 점토를 사용하였기 때문에, 산화 티타늄의 함량이 현저하게 적게 나타나는 것을 알 수 있다. 이 논문의 방법과 결과들을 토대로 앞으로 이루어질 많은 발굴과 분석 자료들이 계속 축적될 수 있다면 더욱 좋은 비교 연구가 가능 할 것이다.

중심어: 한국전통도자기, 한국자기, 한국도기, 전통도자기의 태토성분, 전통도자기의 유약성분, 청자, 백자

ABSTRACT The composition of Chinese ceramic shards has been the subject of analysis in Europe, beginning in the 18th century, and in China from the 1950s. Scientific studies of traditional Korean shards commenced in the United States and Germany in the 1980s, and studies within Korea began in the 1990s. From analysis of a large systematically collected dataset, the composition of porcelain produced during the Koryŏ dynasty, including 21 celadon and 10 whiteware groups,

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was characterized and compared with that of Chinese ceramics. The average composition of the body and glaze of several shards (usually three to five) from each group was determined, enabling comparisons between groups. The results show that the majority of groups were derived from mica-quartz porcelain stone, which was commonly used in Yuezhou, Jingdezhen, and other southern Chinese kilns. The composition of glazes includes clay and flux components; the latter were typically wood ash and limestone, initially as burnt but later as crushed forms. The earliest of the Kangjin glazes contained substantially less titanium oxide than did the Yuezhou glazes, which were typically formulated from body material and wood ash. The present study provides a comparative framework for the growing number of analytical investigations associated with excavations occurring in Korea.

Key Words: Korean traditional ceramics, Korean porcelain, Korean stoneware, Body composition of traditional ceramics, Glaze composition of traditional ceramics, Celadon, Whiteware

1. Introduction

As a result of the numerous parameters involved in the physical and chemical transformation of clay into decorative figures and utensils employed in daily life, the history of ceramics technology has been characterized principally by trial-and-error. However, well before Antoine Laurant Lavoisier (1743-1794) published *Traite Elementaire de Chimie* in 1789, introducing a new era of chemistry, the principles and methods of chemical analysis had already been applied to porcelain materials. In efforts to identify the secret material of Chinese porcelain, termed ‘white gold’, many centers in Europe undertook systematic analyses. In 1712 and 1722 the Jesuit missionary Pere D’Entrecolles sent a very large number of porcelain shards from the Jingdezhen Chinese porcelain center to the famous chemist Rene A. P. de Reaumur for analysis. The results identified two components; these were infusible kaolin and fusible chinastone.[1] Even after Chinese-style hard-paste porcelain was successfully developed in Europe, compositional analyses continued throughout the 19th and 20th centuries in countries including Sweden, France, England. and Russia. In the 1950s Chinese scientists began analysis of Chinese porcelain,[2] and in 1982 the Shanghai Institute of Ceramics sponsored a triennial series of international conferences on ancient ceramics.[3]

In 1988 the United States Materials Research Society initiated the ‘Materials Issues in Art and Archaeology’ division, and a conference in 1990 included a short paper on Korean ceramics. [4] A more substantial work, appearing in 1989, showed that foreign interest in Korean ceramics had begun in earnest.[5] At approximately this time our laboratory (in Korea) began a systematic analysis of Korean ceramics.[6-10] The chemical composition and microstructural characteristics of more than 1,500 Korean porcelain shards, both from museum collections and recent archaeological excavations (in cooperation with ceramics historians), have now been analyzed.

From the resulting data, the general chemical characteristics of the various types of Korean ceramics can be deduced and compared with those of Chinese ceramics. In this study we describe the comparative characteristics of celadon and whiteware porcelain produced during the Koryŏ dynasty (918-1392 AD). Three archaeological excavations in Kyonggido (Sŏri in 1984, 1987, and 1988; Bangsandong in 1997 and 1998; and Chungamni in 2002 and 2003) demonstrated that the initial development of porcelain technology during the Koryŏ dynasty involved production of both whiteware and celadon, even though this period was previously known only for remarkable celadon porcelain. Celadon and whiteware shards from excavations at Sŏri and Bangsandong have been characterized archaeologically, and are central to the present study.

2. Experimental

2.1. Selection and Archaeological Background of Shard Samples

The locations of kilns from which analyzed shards were originally excavated are identified by numbers in Figure 1,

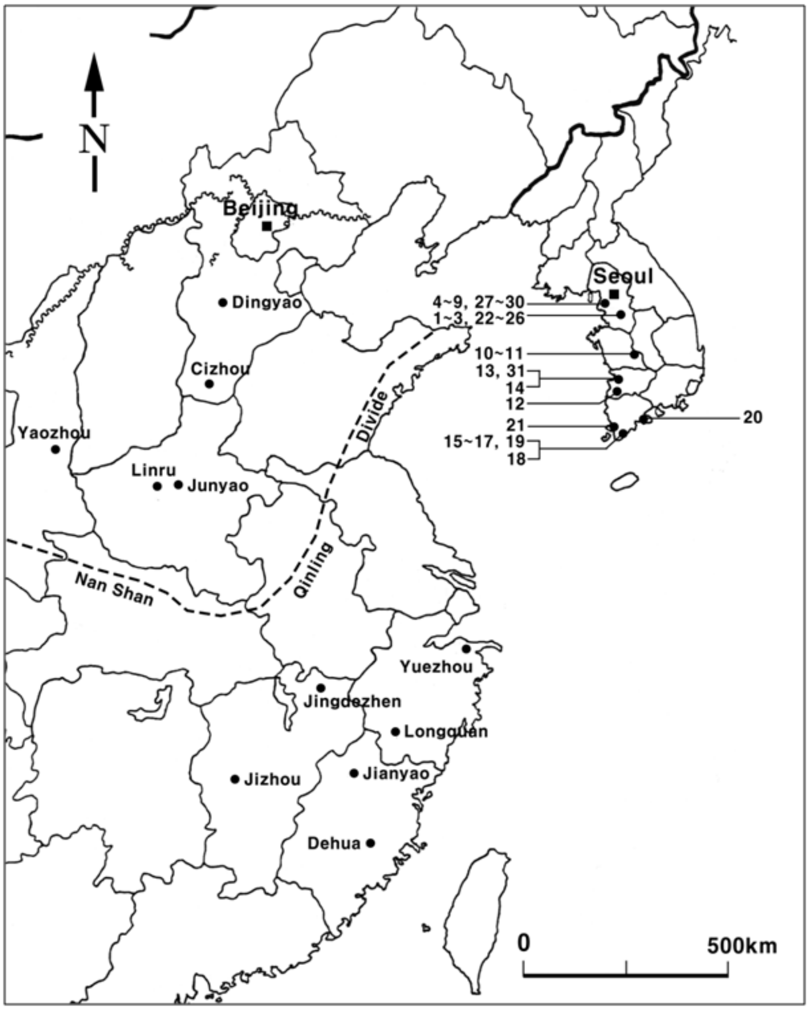

Figure 1. Map of kiln locations from which the analyzed shards were collected. The map also shows the line of Nan Shan Qinling Divide and important kilns in China.

which correspond to the group numbers in Table 1 and the graphs in Figures 3–7. Figure 1 also shows the most important historical Chinese kilns. Table 1 provides archaeological information on kilns from where porcelain shards were excavated; their locations and periods of activity; the years of excavation; and the museums in charge of excavation (which provided shards for analysis). When possible, site-specific details are provided, including archaeological layers in which shards were found, and any notable decorative characteristics. Table 1 also includes results of compositional analysis of the body and glaze of the porcelain shards. Because of the heterogeneous nature of shard composition, 3-5 shards from each group were analyzed, and analytical results were averaged. In the case of the Sadangni group (group 19), which included some of the finest *sanggam* celadon produced over a period of three centuries, up to 26 shards were analyzed. The numbers of shards analyzed within each group are shown in Table 1 in parenthesis below the group number.

Relative to the Sŏri and Bangsandong kilns, the historically important Kangjingun and Puangun kilns were poorly represented in our analysis; only five groups spanned the five

Table 1. Archaeological information on the analyzed shards and their composition of body and glaze (C: century; E: early; M: middle; L: late; No.: Number of shards analyzed for the average value of composition).

Group (No.)	Kiln address							Specific location			Shard type				Operational date (C)				Excavational year				Shard provider				
	Body composition (wt.%)														Glaze composition (wt.%)												
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	L.O.I.	Total	SiO_2	R_xO_y	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	Total	SiO_2	Al_2O_3
CELADON																											
1	Kyŏnggido Yongingun Idongmyŏn **Sŏri**							IV layer			pre-haemurigup				L 9				1984, '87, '88				Ho-Am Art Museum				
(3)	72.53	18.40	2.89	0.98	0.34	0.91	2.61	1.07	0.02	0.03	0.07	99.85	6.69	0.58	61.00	13.82	2.24	1.85	15.73	1.15	1.68	0.95	0.40	0.74	99.56	2.54	0.34
2	Kyŏnggido Yongingun Idongmyŏn **Sŏri**							III layer			pre-haemurigup				10				1984, '87, '88				Ho-Am Art Museum				
(3)	73.20	17.77	2.69	0.73	0.31	1.08	3.23	0.72	0.02	0.02	-0.13	99.65	6.99	0.58	59.52	14.20	3.04	3.98	12.78	1.28	1.93	0.82	0.43	1.81	99.81	2.38	0.33
3	Kyŏnggido Yongingun Idongmyŏn **Sŏri**							III layer			Chinese style haemurigup				10				1984, '87, '88				Ho-Am Art Museum				
(3)	74.12	17.03	2.61	0.77	0.31	1.12	3.21	0.77	0.02	0.03	-0.04	99.93	7.39	0.62	58.60	13.94	2.41	3.36	15.38	1.37	1.98	0.71	0.50	1.93	100.18	2.19	0.31
4	Kyŏnggido Sihŭngsi **Bangsandong**							S1E1							L9~L10				1997~'98				Haegang Ceramics Museum				
(3)	76.17	15.47	1.84	0.71	0.58	0.95	3.13	0.70	0.02	0.04	0.35	99.97	8.36	0.64	60.02	13.66	2.25	1.58	16.97	1.09	1.78	0.89	0.67	0.84	99.75	2.39	0.32
5	Kyŏnggido Sihŭngsi **Bangsandong**							N1E3, top layer							L9~L10				1997~'98				Haegang Ceramics Museum				
(3)	74.80	16.55	2.54	0.86	0.36	0.83	3.02	0.82	0.02	0.04	0.29	100.11	7.67	0.61	60.91	14.29	2.72	2.57	13.11	1.15	2.36	0.88	0.39	1.31	99.71	2.64	0.37
6	Kyŏnggido Sihŭngsi **Bangsandong**							N1E3, middle layer							L9~L10				1997~'98				Haegang Ceramics Museum				
(3)	76.54	14.87	2.00	0.81	0.66	1.26	2.78	0.88	0.02	0.03	0.13	99.98	8.74	0.72	60.79	12.36	1.75	1.53	19.41	1.22	1.43	0.81	0.69	0.65	100.64	2.23	0.27
7	Kyŏnggido Sihŭngsi **Bangsandong**							N1E3, bottom layer							L9~L10				1997~'98				Haegang Ceramics Museum				
(3)	75.08	16.49	2.25	0.75	0.61	1.10	2.73	0.78	0.02	0.03	0.14	99.99	7.73	0.62	62.27	13.64	2.21	1.64	15.44	1.13	1.94	0.87	0.57	0.67	100.36	2.64	0.34
8	Kyŏnggido Sihŭngsi **Bangsandong**							N1E1, middle layer							L9~L10				1997~'98				Haegang Ceramics Museum				
(3)	75.55	16.05	2.12	0.80	0.56	0.99	3.03	0.78	0.02	0.03	0.09	100.01	7.99	0.64	60.36	12.93	2.29	1.84	16.89	1.11	1.69	0.86	0.66	0.81	99.44	2.38	0.30
9	Kyŏnggido Sihŭngsi **Bangsandong**							N1E1, bottom layer							L9~L10				1997~'98				Haegang Ceramics Museum				
(3)	76.22	15.41	2.11	0.83	0.57	0.87	2.75	0.91	0.02	0.04	0.23	99.96	8.40	0.66	60.65	12.90	2.01	1.98	17.23	1.08	1.64	0.95	0.50	0.94	99.87	2.35	0.29
10	Taejŏnsi Chunggu **Kuwandong**							1st celadon kiln							L11~E12				1995				Haegang Ceramics Museum				
(6)	70.54	20.56	2.83	0.83	0.54	0.94	3.04	0.69	0.02	0.04	-0.05	99.99	5.82	0.52	53.27	16.30	1.93	2.42	19.95	0.95	2.78	0.27	0.48	1.53	99.88	1.80	0.32
11	Taejŏnsi Chunggu **Kuwandong**							2nd celadon kiln							L11~E12				1995				Haegang Ceramics Museum				
(6)	69.44	20.87	3.58	0.91	0.43	0.70	3.22	0.70	0.02	0.05	0.05	99.98	5.65	0.52	55.35	14.39	1.67	2.54	19.90	0.61	2.97	0.29	0.53	1.62	99.87	1.87	0.29
12	Chŏllapukdo Koch'anggun Asanmyŏn **Yonggyeri**														E10~E11				1985				Haegang Ceramics Museum				
(5)	75.94	15.67	1.92	0.58	0.31	0.61	2.84	0.93	0.02	0.04	0.67	99.53	8.23	0.55	57.73	13.02	1.63	3.58	18.98	0.64	1.80	0.54	0.70	1.54	100.15	1.94	0.26
13	Chŏllapukdo Puangun Poanmyŏn **Uch'ŏlli**														12~14				1998 (Japanese)				Ewha Woman's University Museum				
(9)	74.03	18.03	1.84	0.61	0.31	0.53	2.70	0.91	0.02	0.03	0.50	99.52	6.97	0.46	58.63	13.61	1.34	1.79	19.48	0.48	3.12	0.24	0.44	0.57	99.70	2.15	0.29
14	Chŏllapukdo Puangun Sannaemyŏn **Chinsŏri**														L11~E12				1990 (Japanese)				Ewha Woman's University Museum				
(3)	74.40	16.99	2.13	0.62	0.39	0.83	2.78	0.91	0.02	0.03	0.46	99.58	7.43	0.54	58.47	14.07	1.61	2.97	16.56	0.73	2.46	0.47	0.56	1.23	99.14	2.21	0.31
15	Chŏllanamdo Kangjingun Daekumyŏn **Yongunni**							Y-36							E10				1980~'82, '91~'92				Haegang Ceramics Museum				
(5)	72.71	18.96	2.50	0.63	0.66	0.68	2.70	0.82	0.01	0.02	0.21	99.90	6.51	0.50	60.01	13.73	1.97	2.32	18.36	0.60	1.72	0.21	0.39	0.92	100.22	2.27	0.31
16	Chŏllanamdo Kangjingun Daekumyŏn **Yongunni**							Y-9							M~L9, 10				1980~'82, '91~'92				Haegang Ceramics Museum				
(5)	73.72	16.85	2.46	0.51	0.54	0.94	3.15	0.73	0.03	0.03	0.26	99.20	7.43	0.58	60.81	14.87	1.83	2.20	15.28	0.77	3.07	0.25	0.36	0.77	100.23	2.55	0.37

Group (No.)	Kiln address								Specific location			Shard type				Operational date (C)				Excavational year			Shard provider				
	Body composition (wt.%)														Glaze composition (wt.%)												
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	L.O.I.	Total	SiO_2	R_xO_y	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	Total	SiO_2	Al_2O_3
17	Chŏllanamdo Kangjingun Daekumyŏn **Yongunni**								Y-63							M~L9				1980~'82, '91~'92			Haegang Ceramics Museum				
(5)	70.04	21.29	2.78	0.75	0.32	0.20	2.34	0.98	0.01	0.03	0.84	99.59	5.58	0.40	58.94	15.81	2.08	1.98	16.91	0.65	2.29	0.48	0.35	0.41	99.89	2.38	0.38
18	Chŏllanamdo Kangjingun Ch'ilryangmyŏn **Samhŭngni**								H3							E10				2001~2002			Haegang Ceramics Museum				
(4)	69.80	20.39	3.05	0.64	0.50	0.46	2.56	0.85	0.02	0.04	0.82	99.10	5.81	0.45	62.10	15.09	1.86	1.67	14.52	0.99	2.46	0.28	0.28	0.57	99.82	2.83	0.40
19	Chŏllanamdo Kangjingun Daekumyŏn **Sadangni**															12~14				1964-'92, 2001~'02			Haegang Ceramics Museum				
(26)	73.06	18.63	2.36	0.64	0.37	0.66	3.19	0.80	0.02	0.03	0.25	100.01	6.66	0.50	56.71	14.17	1.73	1.70	20.82	0.70	2.67	0.27	0.55	0.60	99.92	1.97	0.29
20	Chŏllanamdo Kohŭnggun Duwonmyŏn **Undaeri**															L9~L10				1984, '86, '89, 2000~'01			Haegang Ceramics Museum				
(5)	75.94	15.90	2.31	0.51	0.37	0.90	2.37	0.84	0.02	0.03	0.46	99.66	8.11	0.54	60.12	13.72	1.57	1.55	19.58	0.89	1.50	0.46	0.39	0.39	100.18	2.27	0.31
21	Chŏllanamdo Haenamgun Sanimyŏn **Chinsanni**								17th kiln							L10~E11				1991			Mokpo University Museum				
(7)	74.09	17.93	2.45	0.70	0.38	0.66	2.34	1.06	0.02	0.03	0.34	100.01	7.01	0.51	57.53	13.67	2.53	2.85	16.02	2.10	2.24	1.00	0.76	0.98	99.68	2.08	0.29
KORYŏ WHITEWARE																											
22	Kyŏnggido Yongingun Idonmyŏn **Sŏri**								IV			pre-haemurigup				L9				1984,'87, '88			Ho-Am Art Museum				
(3)	70.64	21.22	1.41	0.37	0.10	0.59	4.47	0.02	0.02	0.02	1.04	99.91	5.65	0.37	57.11	14.43	0.75	1.71	20.97	0.95	2.84	0.14	0.26	0.85	100.00	1.99	0.30
23	Kyŏnggido Yongingun Idonmyŏn **Sŏri**								III			pre-haemurigup				10				1984,'87, '88			Ho-Am Art Museum				
(3)	73.22	18.31	1.40	0.27	0.12	1.21	4.98	0.03	0.03	0.02	0.31	99.92	6.79	0.51	57.50	15.02	1.26	2.58	16.06	1.66	3.32	0.12	0.40	1.64	99.57	2.18	0.34
24	Kyŏnggido Yongingun Idonmyŏn **Sŏri**								III			Chinese style haemurigup				10				1984,'87, '88			Ho-Am Art Museum				
(3)	72.84	18.53	1.38	0.38	0.08	0.51	5.13	0.05	0.02	0.02	1.00	99.96	6.67	0.46	58.13	13.73	1.23	2.93	17.21	0.81	3.41	0.11	0.57	1.75	99.87	2.11	0.29
25	Kyŏnggido Yongingun Idonmyŏn **Sŏri**								II			Korean style haemurigup				10				1984,'87, '88			Ho-Am Art Museum				
(3)	74.26	17.95	1.53	0.44	0.26	0.29	4.98	0.11	0.02	0.04	0.13	100.00	7.02	0.48	60.08	14.96	1.57	2.65	13.55	0.53	3.80	0.11	0.54	2.10	99.89	2.57	0.38
26	Kyŏnggido Yongingun Idonmyŏn **Sŏri**								I			modified haemurigup				E11				1984,'87, '88			Ho-Am Art Museum				
(3)	73.90	17.41	1.64	0.50	0.30	0.29	4.61	0.11	0.02	0.05	0.80	99.64	7.20	0.49	58.54	14.65	1.35	2.76	15.71	0.53	3.41	0.15	0.58	2.14	99.83	2.28	0.34
27	Kyŏnggido Sihŭngsi **Bangsandong**								S1E1							L9~L10				1998			Haegang Ceramics Museum				
(3)	73.38	18.04	1.04	0.26	0.16	0.63	5.11	0.01	0.03	0.04	1.36	100.04	6.90	0.46	58.04	13.39	1.06	2.35	18.87	0.81	3.31	0.22	0.50	1.51	100.05	2.06	0.28
28	Kyŏnggido Sihŭngsi **Bangsandong**								N1E3, Middle layer							L9~L10				1998			Haegang Ceramics Museum				
(3)	72.57	19.61	1.27	0.40	0.12	0.67	4.33	0.01	0.02	0.02	0.97	99.99	6.28	0.40	61.07	16.28	1.23	1.16	15.83	1.09	3.15	0.17	0.61	0.49	101.08	2.65	0.42
29	Kyŏnggido Sihŭngsi **Bangsandong**								N1E3, Bottom layer							L9~L10				1998			Haegang Ceramics Museum				
(3)	73.25	19.18	1.13	0.36	0.14	0.74	4.22	0.03	0.02	0.02	0.90	99.98	6.48	0.39	59.24	14.67	1.05	1.17	18.73	0.95	2.61	0.18	0.62	0.53	99.75	2.31	0.34
30	Kyŏnggido Sihŭngsi **Bangsandong**								N1E1, Middle layer							L9~L10				1998			Haegang Ceramics Museum				
(3)	72.52	20.05	1.37	0.38	0.09	0.72	4.30	0.01	0.01	0.02	0.57	100.06	6.14	0.36	59.48	14.35	1.31	1.12	18.32	1.07	2.72	0.20	0.49	0.73	99.79	2.34	0.33
31	Chŏllapukdo Puangun Poanmyŏn **Uch'ŏlli**															12~14				1998 (Japanese)			Ewha Woman's University Museum				
(4)	75.33	18.41	0.98	0.31	0.10	0.13	4.40	0.11	0.02	0.01	0.73	99.97	6.94	0.46	57.38	12.06	1.10	1.73	21.79	0.10	3.55	0.18	0.11	1.23	99.23	1.95	0.24

centuries of operation of the Kangjin kilns and only four groups represented the three centuries during which the Puan kilns were active. The Kangjin and Puan kilns were discovered in the first decades of the 20th century, and because of their historical importance, have since been sporadically explored on numerous occasions. Publication of excavation results were delayed, [11] or indeed remain unavailable, and both shards and other remains collected have been characterized only poorly. More systematic investigations of the surface remains of the Kangjin and Puan kilns were carried out in the 1990s and the early 2000s.[12,13]

The Sŏri and Bangsandong sites are 2 of approximately 12 of the earliest porcelain sites clustered around central Korea, near Seoul and the Kwangju Chosŏn royal kilns. The other cluster of early sites lies in Korea's southwestern coastal area, in and around Kangjin. Kangjin was a very significant site until superseded in importance by the Sŏri and Bangsandong locations.[14] Kangjin was assumed to be the kiln through which Korea successfully imported the celadon technology from the Yuezhou kiln complex in China. The tea bowls from Kangjin are remarkably similar to those from Yuezhou in general style and glaze color, and both had an unusual footrim, which resembles the halo of the sun and is known by the Korean name *haemurigup*.

However, the possibility that the inland kilns were founded earlier than those in the Kangjin area was raised by results of the Sŏri excavation in the 1980s. [15,16] At the Sŏri site, *haemurigup* tea bowls were excavated from four different layers designated I–IV (numbered from the top). Based on slight variations in the size and shape of the body, the appearance of the internal bottom face, the overall width of the footrim, and the width of the footrim area in contact with the underlying surface, the *haemurigup* style was divided into four types (Fig. 2). The type commonly found in Kangjin, designated the Korean style, was found in the third oldest layer (level II); two different styles were evident in the lower levels. The oldest type, designated 'pre- *haemurigup'*, is not found at Kangjin, and only a very small number of shards from the second oldest type (termed 'Chinese style') was located.

Several questions on these two sets of earliest kilns have become a focus of controversy among scholars investigating the origins of Korean porcelain technology. Did the inland kilns precede the southwestern kilns, as suggested by the apparent sequence of the *haemurigups*? Do the two sets represent importation of technology by different routes, occurring at the same or different times? When and how did actual transfers occur? Who were the sponsors and who were the potters?

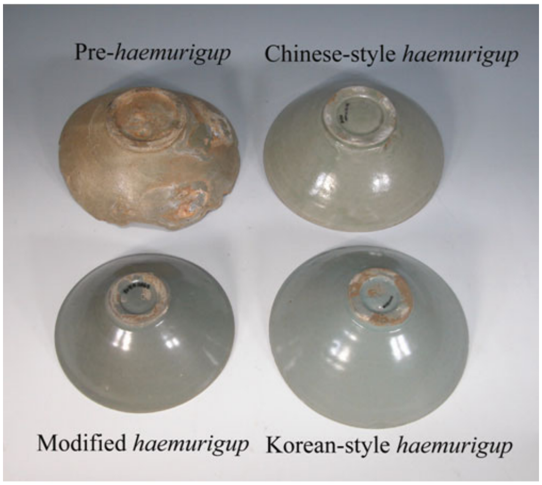

Figure 2. Types of haemurigup tea bowls (Haegang Ceramics Art Museum, Seoul, Korea). In the Sŏri excavation the pre-*haemurigup* bowls are found in the oldest levels (IV and III), the Chinese type occurs in level III, the Korean type in level II, and modified types in levels II and I.

The two sets of kilns, one inland of central Korea and the other on the southwestern coast, experienced very different histories in the development of Korean stoneware and porcelain. All inland kilns, including Kuwandong kiln,[17] had disappeared by the 11th century, whereas Kangjin became a porcelain center and remained so for 5 centuries until the end of Koryŏ dynasty. Many kilns in the southwest (other than Kangjin), including the Undaeri (group 20) and Chinsanni (group 21) kilns also closed, and, in the 12th century, another center was established at Puan. At Kangjin and Puan, porcelain technology became highly centralized and was supervised by government officials. With the exception of a small amount of whiteware produced mostly at Puan,[13,18] whiteware production was discontinued and celadon technology became indigenized and well established.

This led to three innovations: the famous and unique jade-like *pisaek* glaze; the technique of inlaid (*sanggam*) decoration; and the extremely complex decorative technique known as copper red.

From the outset, the inland and southwestern kilns exhibited different characteristics and firing practices. Kangjin and other southwestern kilns were similar to those built for *togi*; a term describing unglazed earthenware produced in vast amounts to the time of the United Silla dynasty (AD 668–935). The kilns were much smaller than those of the inland, and were constructed of mud clay mixed with rocks rather than with bricks. Moreover, the ceramics were fired twice, once prior to glazing and once afterwards. The large brick kilns and the one-step firing method of the inland kilns were all directly imported from China. With the closure of the inland kilns these practices disappeared and more local methods became established; these remained the traditional techniques for production of all ceramic types during the Koryŏ dynasty and throughout the Chosŏn dynasty.

2.2. Experimental Procedures

As the analytical methods used in this study have been reported in detail by Koh Choo and colleagues several times, such as in a publication on Sŏri porcelain, only a brief outline and specific conditions are described here. [9] The composition of shard bodies was determined using a PW1480 X-ray fluorescence sequential spectrometer (Philips Inc.) located at the Korea Basic Science Institute. The glaze was removed from the body, which was next powdered and formed into cylindrical beads. The analytical conditions were 40 kV and 30 mA.

In all glaze analyses, shards were embedded in epoxy resin and polished to expose cross- sections. Two different sets of instruments and experimental conditions were used to measure glaze composition from these samples. Shards from Sŏri and Bangsandong were examined using a JEOL 5800-LV scanning electron microscope (SEM) operating at 15 kV and 2.5 nA. [9] The average of 10 measurements in an area 60 × 60 μm^2 is reported for each shard. Other shard groups were analyzed using an electron probe microanalyzer (Jeol Superprobe JXA-8600SX) equipped with an SEM and an EDS (Oxford Pentafet$_{ATW}$ Detector). Analysis conditions were 15 kV and 2.5 nA. The average of 4-6 measurements in an area of either 48 × 36 μm^2 or 34 × 25 μm^2 is reported for each shard.

3. Results and Discussion

3.1. Comparison of Body Composition

Seger graphs of body and glaze compositions are shown in Figures 3 and 4, respectively. To calculate Seger values, all oxides other than Al_2O_3 and SiO_2 were included in the R_xO_y term. The values for the bodies of Korean ceramics were found to be in the same range as that of celadon from southern China, the Seger values of which are shown as gray circles in Figure 3.[19,20] The Shangyu, Shaoxing, and Shanglinhu areas of the Yuezhou complex in Zhejiang province were the most important centers of celadon production in China to the period of the late Tang (AD 618–906) and Five (AD 906–960) dynasties; the Longquan area in Zhejiang province became more active from approximately the 11th century.

The similarity in body composition of Korean and southern Chinese ceramics (Figure 3) stems from the similar geology of the two areas, as shown in the map (Figure1). China is divided into two distinct clay zones (north and south) along the so-called Nan Shan Qinling line. Most of Korea occurs south of this line because the landforms of the two regions are aligned from southwest to northeast.[21] Sites identified above this line have clays rich in kaolinite, whereas weathered igneous rocks of quartz and hydromica, with minor amounts of primary clay and feldspar, are typical of sites identified below the line. The hard paste material that occurs in Korea and south China has all three of the tri-axial properties necessary for firing ceramics at high temperature. Hydromica provides the required plasticity and fluxing properties, whereas quartz contributes the refractory qualities necessary for high-temperature sintering. Appropriate mechanical treatment alone often facilitated production of Korean ceramics. Such materials, termed *tanmi* (‘single taste’), were used continuously throughout the Koryŏ and

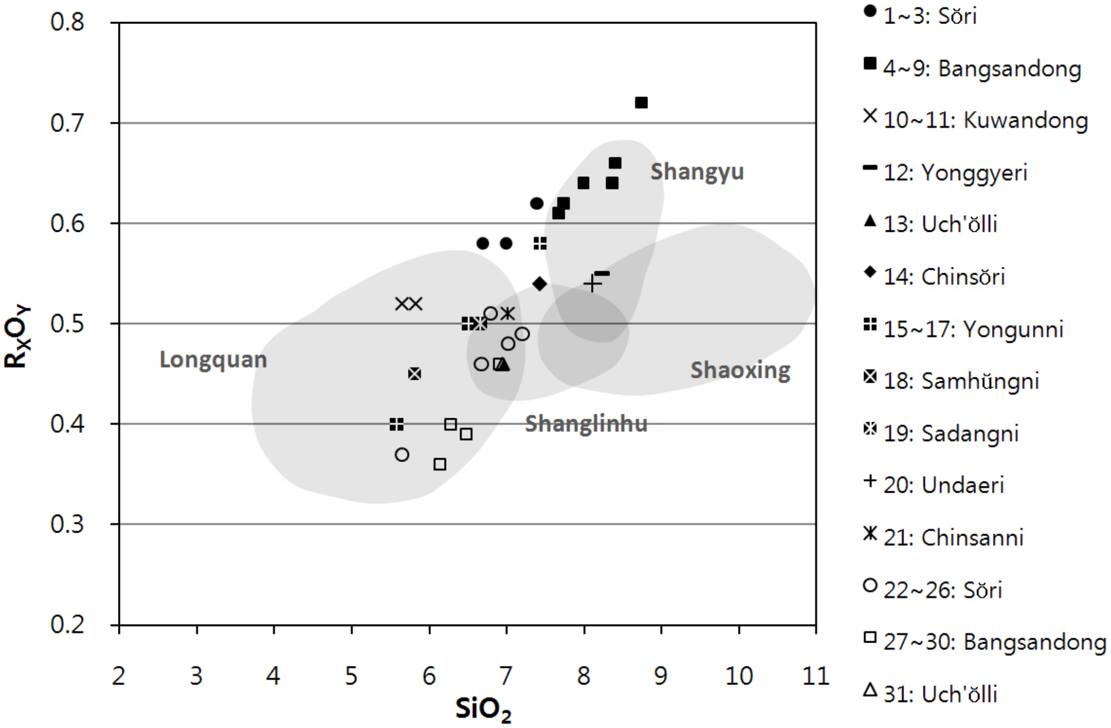

Figure 3. Seger graph of body compositions (SiO_2 as a function of R_XO_Y).

Chosŏn dynasties. Such materials are also used as a basic ingredient in formulation of glaze batches.

Koryŏ whiteware from Sŏri and Bangsandong appears in the same section of the Seger graph as celadon from Kangjin and other southwestern kilns. However, celadon from Sŏri and Bangsandong is shown at higher points and further to the right. The elevated values of SiO_2 (6–9) and R_xO_y (0.5–0.7) in Sŏri and Bangsandong celadon reflect the rather unusual composition among Korean ceramics. Such materials have the lowest Al_2O_3 content of all Korean kiln products analyzed to date [22] and also have a slightly higher flux content, especially of sodium oxide, than shown by the product of other kilns of the Koryŏ dynasty. These compositional characteristics must have been key factors enabling potters to successfully vitrify their wares with only one firing (rather than two), as was necessary in the southwestern kilns. In addition, vitrification would have been possible at a somewhat lower firing temperature.

Although the Seger value range is similar, small differences between the content of minor oxides in whiteware from the central kilns of Sŏri and Bangsandong, and the celadon from Kangjin and other southwestern kilns, are apparent. The levels of iron and titanium oxides in southwestern celadon are higher (around 2 wt.% and 1 wt.%, respectively), whereas the K_2O content is lower (around 2–3 wt.%), than in whitewares. Longquan celadon is unique among Chinese celadons in that the content of iron and titanium coloring agents is as low as seen in the whitewares. The body material from Longquan area is better suited for making of whiteware, as this clay is very low in both iron and titanium oxides. Even when whiteware became popular in China, as a result of successful production at the nearby Jingdezhen kiln, Longquan potters continued to make celadon by adding clay rich in iron and titanium to their whiteware material. [23]

3.2. Comparisons of Glaze Composition

In the glaze Seger graph (Figure 4), all Korean celadon and whiteware groups cluster to the left of Yuezhou celadon. The overlap of Seger values between Koryŏ and Yuezhou glazes indicates that the glaze formulations employed had similar basic ingredients, and that the firing temperature range was similar in both regions. The small range of Seger values for Korean glazes implies that all Koryŏ kilns (for both celadon and whiteware), and those in the southwest, used the same ingredients and methods to make glaze. However, Figures 5–7 show that Koryŏ glaze batches were diverse, and formulated from a wide variety of materials. In some ways, the celadon glazes from Kangjin and other southwestern kilns appear to have more similarity with glazes from Longquan kilns and northern celadons from the Yaozhou, Ru, and Linru kilns, compared to Yuezhou glazes. Figures 5–7 include data on these Chinese kilns (Yuezhou, Longquan, Yaozhou, Ru and Linru), selected at random from Chinese research publications.[24,25]

In both Korea and China, glaze batches were usually made by mixing flux and clay material. As shown in the analysis of calcium and alkali oxides (Figure 5), the chief fluxing ingredient in most Korean glazes was calcium oxide, as was also true for most high-fired Chinese glazes (Zhang, 1986).[26] Chinese glazes have been categorized[27] into four types according to the content of calcium oxide: high lime, lime, lime-alkali, and acid rock. Based on this system, most celadon and whiteware glazes used in Koryŏ ceramics can be categorized as high-lime, although some are lime; the typical values established by Wood are indicated by large circles in Figure 5. The alkali content in whiteware glazes from Sŏri and Bangsandong kilns is higher than that in the celadon glaze from the Kangjin and other southwestern kilns, reflecting the elevated level of sodium and potassium in the former relative to the latter. The alkali content in Chinese celadons is lower than in Korean celadons.

When fired at a high temperature and cooled rapidly, the lime content in high-lime and lime glazes produces a

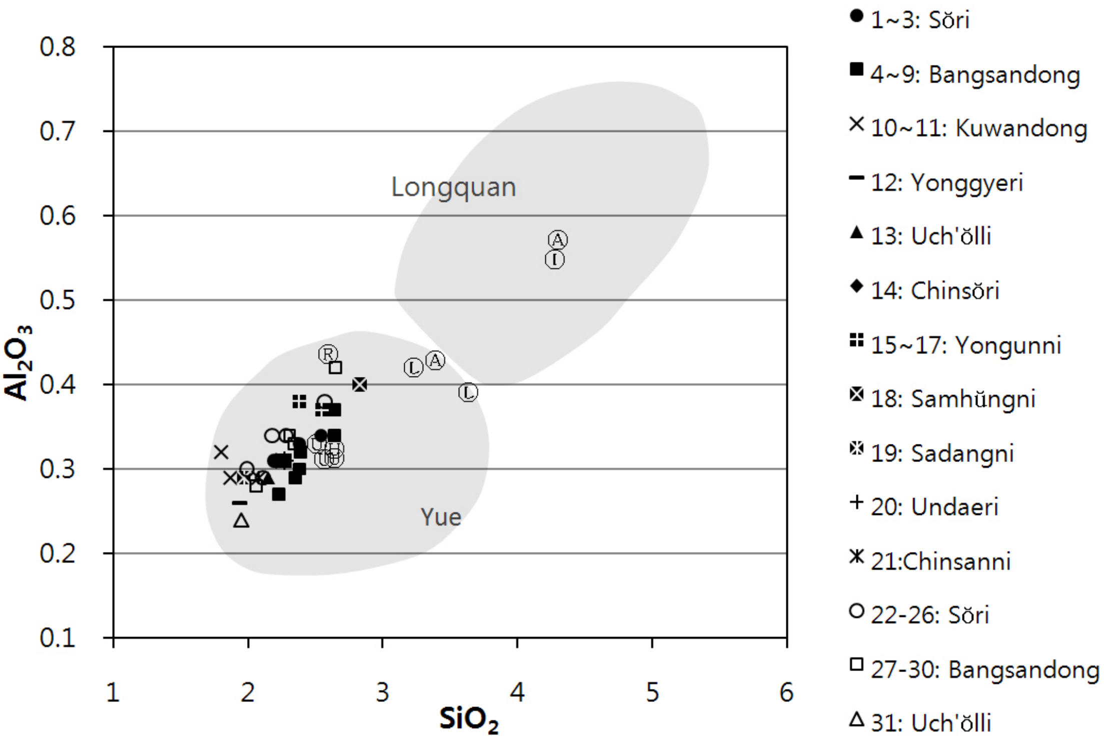

Figure 4. Seger graph of glaze compositions (SiO_2 as a function of Al_2O_3). Chinese data are shown as lettered points; Ⓤfor Yuezhou, Ⓛfor Longquan, Ⓐfor Yaozhou, Ⓡfor Ru, and Ⓘ for Linru.

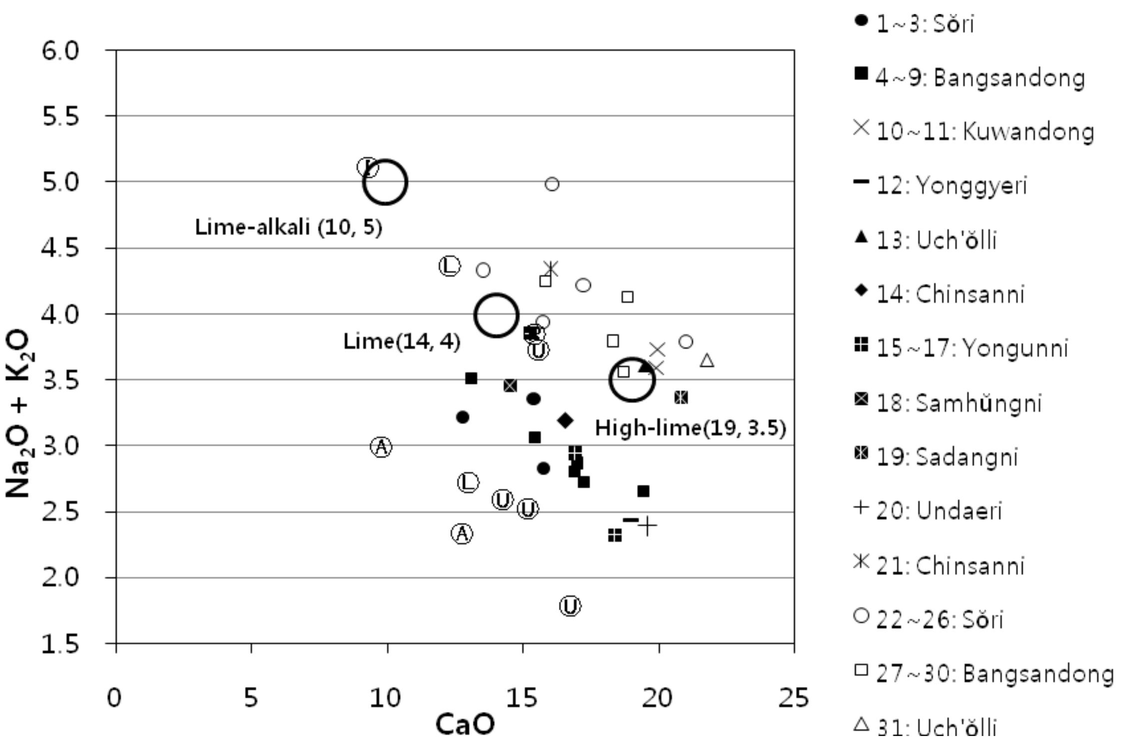

Figure 5. CaO content as a function of $Na_2O + K_2O$ in the glaze. Chinese data are shown as lettered points; Ⓤfor Yuezhou, Ⓛ for Longquan, Ⓐ for Yaozhou, Ⓡ for Ru, and Ⓘfor Linru. The composition values categorized by Wood as high-lime, lime, and lime-alkali are indicated by large circles.

transparent glaze, revealing decorations underneath the glaze, such as incised and molded features. Transparent glazes were ideal for the underglaze inlay techniques developed by Koryŏ potters in the 12th century, and continued in use until the end of the dynasty at Kangjin Sadangni and Puan Uch' ŏlli. The high-lime glazes used for both celadon and whiteware at these inlay centers contained calcium oxide at concentrations up to 20 wt.%, or even higher.

Two major sources of calcium were wood ash and limestone, employed in a burnt (glaze ash) or crushed form. The difference between wood ash and limestone is that the former contains three oxides: P_2O_5, MnO, and MgO. Glazes with high levels of these oxides are likely to have been produced using a greater portion of wood ash compared to glaze ash or crushed limestone. Glaze ash contains some wood ash from the burning process; ashes with a high CaO content and low levels of P_2O_5, MnO, and MgO are likely to have been prepared using burnt limestone as a fluxing ingredient.

Figures 6a and 6b show P_2O_5 content as a function of CaO and MnO levels, respectively. These data suggest that differing proportions of wood ash and limestone were mixed with clay material at various Korean kilns. Both celadon and whiteware from the Sŏri kilns have high P_2O_5 content (> 1.5 wt.%), and were almost certainly produced using wood ash alone. Most groups circled in Figure 6a have P_2O_5 concentrations of 0.5–1.0 wt.% and CaO levels of 15.0–21.0 wt.%. These groups likely used glaze ash or crushed limestone in various proportions, in addition to (or in the absence of) wood ash. Only one of four Yuezhou shards, and the Ru shard, are found in this circle, at the lower end of CaO content.

By the 10th century, the use of limestone as glaze ash, or in the crushed form, was favored over wood ash as the main flux material at major Chinese kilns. The high CaO to P_2O_5 ratio of Bangsandong and Yongunni (group 17) glazes suggest that glaze ash was used in Korea, too, in the 10th century. Later, limestone was used to augment the calcium

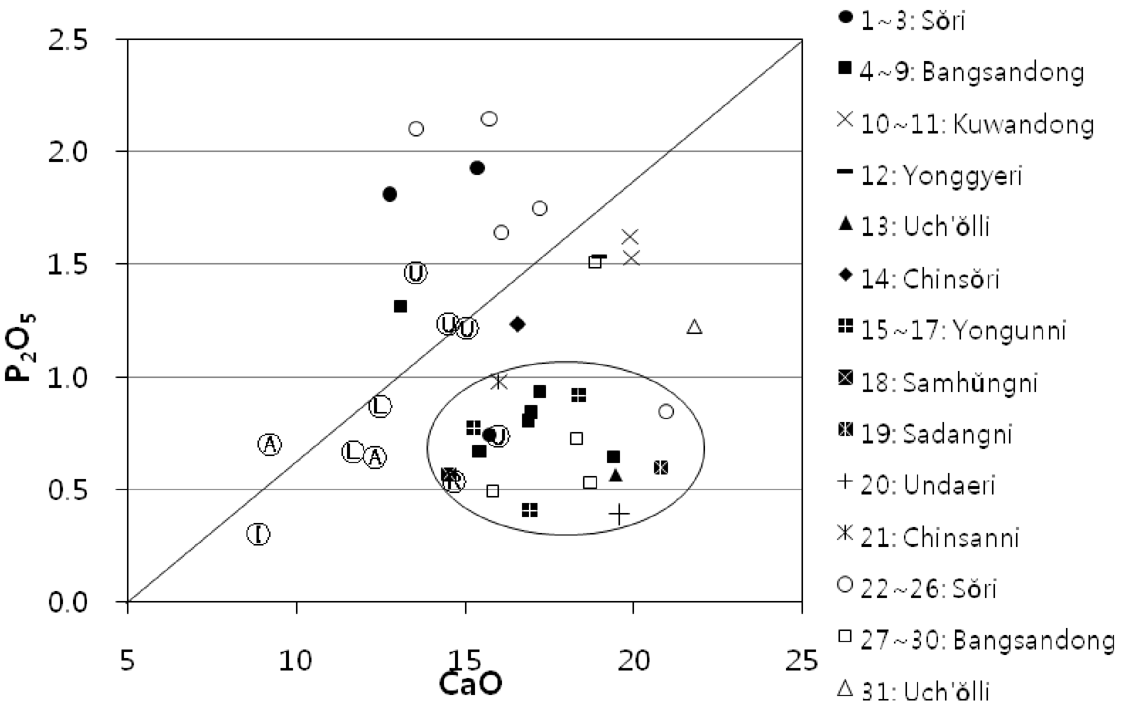

Figure 6a. CaO content as a function of P_2O_5 in the glaze. Chinese data are shown as lettered points; Ⓤfor Yuezhou, Ⓛfor Longquan,Ⓐfor Yaozhou, R for Ru, andⒾfor Linru.

content at the two celadon inlay centers of Kangjin Sadangni (group 19) and Puan Uch' ŏlli (group 13). To best display inlaid decorations it was necessary to limit the level of bubble-creating phosphorus but with maintenance of a high calcium content (around 20 wt.%).

However, any suggestion of limestone use in Bangsandong glazes should be treated cautiously in light of the fact that the neighboring Sŏri site used wood ash almost exclusively. In fact, the unusually high level of MnO with respect to P_2O_5 in Figure 6b shows that the amount of wood ash in the Bangsandong groups (and the Sadangni and Uch' ŏlli groups) should be higher than the low P_2O_5 levels suggest. The trees used to make wood ash or glaze ash at these centers were likely to have been poor in P_2O_5 and rich in CaO and MnO. The composition of the ash of chestnut and birch trees, for example, has these characteristics.[28] The ash of pine and oak trees is rich in oxides of Ca, P, and Mn, and such trees are quite common in Korea. The MnO content has previously been reported to be higher in Sadangni and Uch' ŏlli glazes than in typical Chinese celadon glazes,[5,29] and Figure 6b shows that the MnO level in celadon from other Korean kilns is higher than in Chinese celadon. The Mn-rich trees provided high levels of MnO, which made Korean celadon appear grayer than Chinese celadon. However, despite use of Mn-rich wood ash, the unusually high levels of lime in the transparent glazes overlaying inlaid celadon are almost certain to result from the use of limestone in both burnt and crushed forms.

Whereas the composition of Bangsandong and Sŏri glazes are quite distinct, interesting crossovers between the two kilns are evident. The composition of the earliest celadon (group 1) and whiteware (group 22) glazes from Sŏri fall in the general composition range of Bangsandong glazes, and the composition of the second earliest celadon (group 5) and the earliest whiteware glazes from Bangsandong (group 27) appear in the composition range of Sŏri glazes. Both of these sites continued to produce ceramic wares for over 100 years, during which time the species of trees available for the making of wood and glaze ash must have varied. It is also very likely that potters from the two kilns interacted.

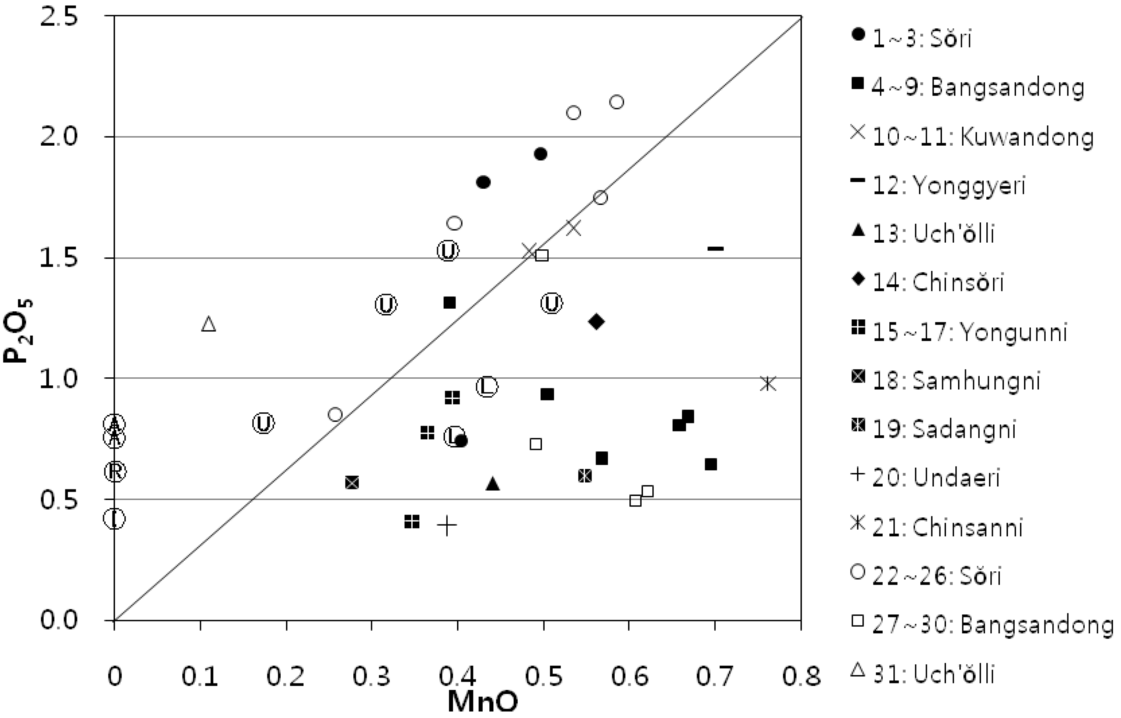

Figure 6b. MnO content as a function of P_2O_5 in the glaze. Chinese data are shown as lettered points; Ⓤfor Yuezhou, Ⓛfor Longquan, Ⓐfor Yaozhou, R for Ru, andⒾfor Linru.

The types of clay material mixed with flux ingredients are reflected in the TiO_2 content of the ceramic body, as a function of TiO_2 level in glazes (Figure 7). Two unusual findings show that Korean glaze technology was innovative with respect to choices of clay material. First, for both celadon and whiteware the Sŏri and Bangsandong glazes contain levels of TiO_2 and Fe_2O_3 as high as or higher than seen in the bodies. These elevated levels of titanium and iron oxide in whiteware, produced an ivory hue, and, in many cases, a green shade similar to that obtained using celadon glazes. Such materials and celadon-glazed whitewares are indistinguishable, and production of the celadon-like effect may have been intentionally sought by early potters at the inland kilns.

Data on three of the four Yuezhou celadon glazes are shown immediately below the Sŏri and Bangsandong celadon numbers in Figure 7, lying along the 80% slope line. Such glaze composition is typical of Yuezhou glazes, which were obtained by combining body material with wood ash in the ratio 8:2.[30] However, Longquan celadon has very little TiO_2 in the body and even less (often only a trace) in the glaze. Following the same approach employed by the Yuezhou kiln, the Longquan body material low in TiO_2 may have been mixed with flux for glaze production.[23] If it is assumed that potters at Sŏri and Bangsandong used the same practice of mixing body material with flux ingredients, what was the source of additional titanium and iron oxides in glaze? In the case of whiteware glaze it is likely that a small proportion of celadon body material was added. However, what iron- and titanium-rich material was used to produce the celadon glaze?

One explanation might be that the wood or glaze ash in this region contained more titanium and iron oxides than was usual. Another possibility is that the Sŏri and Bangsandong potters found and added a glaze stone rich in iron and titanium oxides. Glaze stone is basically the same as weathered quartz and hydromica porcelain rock, but is usually finer grained and commonly has a higher feldspar content. During the Chosŏn dynasty this material was regularly used for glazing at the royal kilns, located near the inland Koryŏ kilns, in the

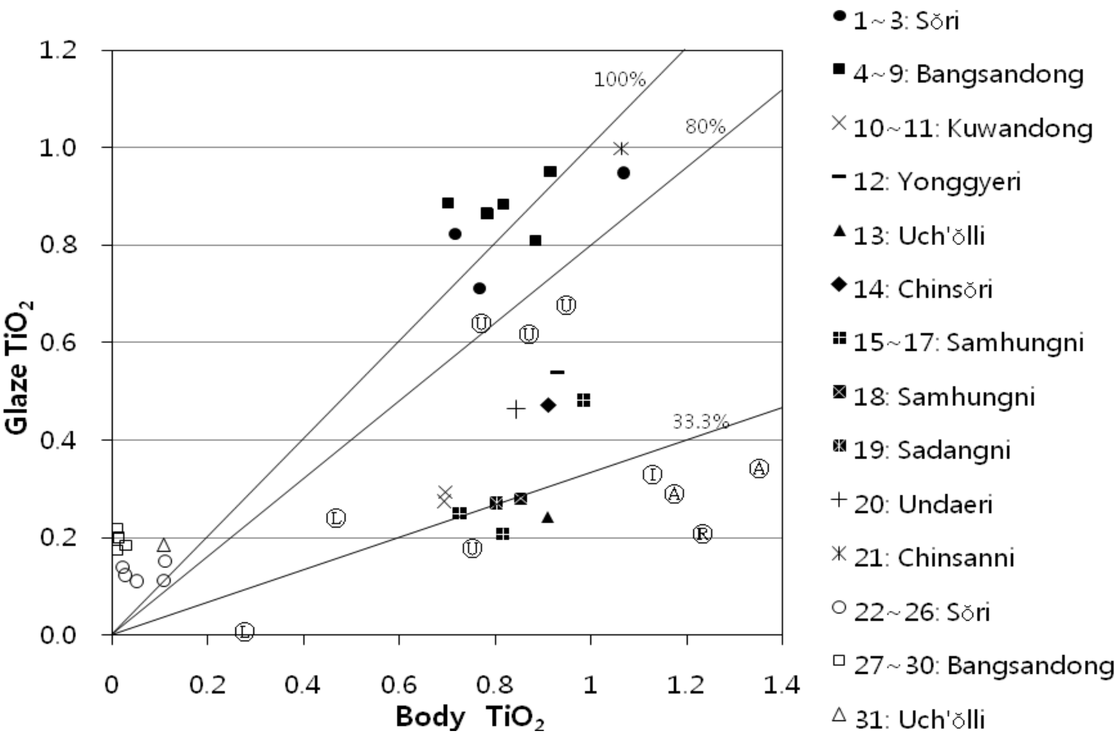

Figure 7. TiO_2 content in the body as a function of that in the glaze. Chinese data are shown as lettered points; Ⓤfor Yuezhou, Ⓛfor Longquan, Ⓐfor Yaozhou, Ⓡfor Ru, andⒾfor Linru.

central region of the country. This material was also used to make *yingqing* in Jingdezhen in the 13th and 14th centuries; [23] in Korea the substance is termed *multo* (water clay). If, indeed, a type of glaze stone was used in Sŏri and Bangsandong to enrich glaze composition of iron and titanium coloring agents, this perhaps represents one of the first uses of this material worldwide.

The second unusual finding with respect to innovation in Korean glaze technology is specific to the Kangjin and other celadon kilns on the southwestern shore. The amount of TiO_2 in celadon glazes is only 30-50% of that in the body. These results confirm the finding of such low level found for Kangjin shards in an earlier work. The quantity of TiO_2 in the glaze is much too small to have been derived from the mixing of body material with flux ingredients, as practiced in Yuezhou and Longuan. Rather, as Figure 7 shows, these low values are closer to those of the glazes from the northern celadons of Yaozhou, Ru and Linru. At these kilns clay material other than that used for the body must have been used. In Yaozhou a stone called *fuping stone* is believed to have been used, but the material used in other Chinese kilns is yet to be identified. In Kangjin the use of a porcelain stone appropriate for whiteware body material has been suggested.[23,31] Indeed, a large mine of porcelain stone appropriate for the whiteware body material has been found close to the celadon kilns. As this material was essentially free of TiO_2, the Kangjin potters could combine it with celadon body material to obtain the desired level of TiO_2. Study of a 17th century whiteware kiln, discovered in the Kangjin area in 2007, indicates that mines such as this were used to produce whiteware in a region where large quantities of celadon had been produced in the previous 500 years.

4. Conclusion

This study of Koryŏ celadon and whiteware materials established several general characteristics of these ceramics. The systematic data compilation and analysis provides the foundation for detailed comparisons of whiteware and celadon ceramics from Sŏri and Bangsandong with celadon from southwestern kilns, and with Chinese ceramics.

The Seger values of the bodies of Koryŏ ceramic wares overlap with those from the Yuezhou and Longquan kilns in southern China. This is a consequence of the common landform that stretches southwest to northeast from southern China to the Korean peninsula. However, within the narrow range of values resulting from the common use of weathered mica–quartz stone, the celadon from Sŏri and Bangsandong (central Korea) is more siliceous and more highly fluxed than either the whiteware from the same region or celadon from southwestern kilns.

The Seger values for the glazes of all three types of Koryŏ ceramic wares (celadon and whiteware from Sŏri and Bangsandong, and celadon from Kangjin and other southwestern kilns) are very similar, and all overlap with the values for Yuezhou celadon. This suggests that the firing temperature range was similar, but further comparisons suggest several significant differences. The Sŏri and Bangsandong kilns closely followed the Yuezhou kilns in mixing body material with flux, while the southwestern Koryŏ kilns used a clay material other than that used for making the body, as was practiced at the northern Chinese kilns of Yaozhou, Ru and Linru. The difference in material characteristics between the two regions is further evidence of the strong influence of Yuezhou practices on the inland kilns of Sŏri and Bangsandong, relative to the southwestern kilns around Kangjin.

In Sŏri and Bangsandong the source of the high TiO_2 and Fe_2O_3 content may be a glaze stone rich in these oxides. This raises the possibility that this important practice, which was later a feature of the Chosŏn royal kilns and in Jingdezhen in China, was used early in the development of ceramic technologies in Korea. The substantially lower TiO_2 content in the glazes of Kangjin and other southwestern kilns was a result of the use of a porcelain stone that was suitable for production of the body of whiteware ceramics. The use of a transparent high lime glaze with higher concentrations of MnO and lower concentrations of TiO_2 than in Chinese celadons enabled development of the beautiful *pisaek* glaze and inlaid decorations that are a unique and original characteristic of Korean ceramic technology.

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