Principal Component Analysis of Chinese Porcelains from the Five Dynasties to the Qing Dynasty

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This is a study of the possibility of identifying antique Chinese porcelains according to the period or dynasty, using major and minor chemical components (SiO_2, Al_2O_3, Fe_2O_3, K_2O, Na_2O, CaO and MgO) from the body of the porcelain. Principal component analysis is applied to published data on 66 pieces of Chinese procelains made in Jingdezhen during the Five Dynasties and the Song, Yuan, Ming and Qing Dynasties. It is shown that porcelains made during the Five Dynasties and the Yuan (or Ming) and Qing Dynasties can be segregated completely without any overlap. However, there is appreciable overlap between the Five Dynasties and the Song Dynasty, some overlap between the Song and Ming Dynasties and also between the Yuan and Ming Dynasties. Interestingly, Qing procelains are well separated from all the others. The percentage of silica in the porcelain body decreases and that of alumina increases with recentness with the exception of the Yuan and Ming Dynasties, where this trend is reversed.

Introduction

Chinese porcelains are usually dated and attributed by employing features [1] such as style, decoration, potting, craftsmanship, material of the body and the glaze, technical defects, foot-rims and base marks. Such subjective methods can at times be unsatisfactory, the tremendous modern-day technological advancement making it possible to produce very good quality reproductions of imperial ware.

In the past there have been attempts to study Chinese porcelains by chemical analysis [2–6] and by the thermoluminescence [7]. Recently much work has been done on trace elements in Chinese porcelains using the non-destructive energy-dispersive X-ray fluorescence technique [8–18].

In this paper, we look into the possibility of identifying antique Chinese porcelains according to the period or dynasty using major and minor chemical components (SiO_2, Al_2O_3, Fe_2O_3, K_2O, Na_2O, CaO and MgO) from the body of the porcelain. Of particular interest are porcelains made in the major porcelain production centre of Jingdezhen. For this purpose we have taken the chemical composition data (SiO_2, Al_2O_3, Fe_2O_3, K_2O, Na_2O, CaO and MgO) of the body material of 66 pieces of Jingdezhen porcelains from the "Comprehensive Summary of the Chemical Composition of Various Ancient Chinese Porcelains" [19]. Table 1 gives the chemical composition of the 66 pieces which come from the Five Dynasties (907–960), the Song (960–1280), Yuan (1280–1368), Ming (1368–1644) and Qing (1644–1922) dynasty.

Principal Component Analysis

The objective of principal component analysis is to take multiple variables (in this case the concentrations of the oxides of 7 major and minor elements: SiO_2, Al_2O_3, Fe_2O_3, K_2O, Na_2O, CaO and MgO) and find linear combinations with principal component 1 having the largest variance, principal component 2 the second largest variance and so on. Therefore, if the data are highly correlated positively or negatively, we can reduce the number of dimensions drastically from 7 to 2 or 3 depending on the data, since in general there is a good deal of redundancy in the original variables, as most of them are measuring similar things.

The concentrations of the oxides of 7 major and minor elements measured on 66 samples from five periods (Five Dynasties = 5, Song = 13, Yuan = 12, Ming = 23 and Qing = 13) form a data matrix $X_{(N \times M)}$ where x_{nm} is the concentration in weight percent of compound m measured on sample n. The mean $\bar{x}_m$ and standard deviation s_m of the concentration of each

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Table 1. Chemical composition of Chinese Porcelains from the Five Dynasties to the Qing Dynasty for Jingdezhen Porcelain bodies. Values in weight percent.

No.	Code	Code in the original	Type of Chinese Porcelain bodies	Dynasties	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	CaO	MgO
1	F1	150	Celadon body	Five Dyn.	75.16	16.92	2.19	2.37	0.14	0.40	0.64
2	F2	T_2-1	White Glaze body	Five Dyn.	77.48	16.93	0.77	2.63	0.35	0.80	0.51
3	F3	T_2-2	White Glaze body	Five Dyn.	76.96	18.04	0.81	2.97	0.25	0.57	0.35
4	F4	TS3-1	White Glaze body	Five Dyn.	74.58	19.24	1.12	2.35	0.56	1.27	0.20
5	F5	TS3-2	White Glaze body	Five Dyn.	75.84	18.33	1.00	2.44	0.40	0.73	0.76
6	S1	JHYQ-1	Yingqing body	Song	75.48	18.37	0.86	2.63	1.34	0.57	0.03
7	S2	JHYQ-2	Yingqing body	Song	74.71	18.40	0.84	2.92	1.00	0.63	0.18
8	S3	JHYQ-4	Yingqing body	Song	75.91	17.24	0.83	2.47	2.15	0.55	0.13
9	S4	JHYQ-5	Yingqing body	Song	77.32	16.54	0.65	2.87	0.39	0.87	0.54
10	S5	JHYQ-7	Yingqing body	Song	74.86	18.14	0.93	2.37	1.83	0.62	0.62
11	S6	JHYQ-8	Yingqing body	Song	75.60	16.31	1.12	2.62	2.68	0.59	0.43
12	S7	S10-1	Yingqing body	Song	75.41	18.15	0.81	2.95	0.46	0.96	0.63
13	S8	S10-2	White Glaze body	Song	76.52	18.80	0.70	2.71	0.29	0.35	0.11
14	S9	S10-5	White Glaze body	Song	75.92	18.53	0.71	2.99	0.49	0.76	0.30
15	S10	S10-6	White Glaze body	Song	77.39	17.54	0.63	2.85	0.21	0.54	0.35
16	S11	S9-1	Yingqing body	Song	76.24	17.56	0.58	2.76	1.02	1.36	0.10
17	S12	S9-2	Yingqing body	Song	74.70	18.65	0.96	2.79	1.49	1.01	0.50
18	S13	S9-5	Yingqing body	Song	77.79	16.16	0.59	3.25	1.14	0.40	0.16
19	Y1	Q4	Blue-and-White body	Yuan	72.75	20.24	0.93	2.87	1.78	0.24	0.15
20	Y2	Q5	Blue-and White body	Yuan	72.64	21.08	0.97	2.69	1.52	0.20	0.18
21	Y3	S9-4	Yingqing body	Yuan	72.94	19.86	0.88	2.11	2.78	0.56	0.30
22	Y4	SHUFU-2	Shufu body	Yuan	73.75	19.52	1.40	3.18	2.03	0.18	0.21
23	Y5	SHUFU-3	Shufu body	Yuan	72.73	20.70	1.16	2.74	2.39	0.14	0.17
24	Y6	SHUFU-4	Shufu body	Yuan	72.15	21.59	1.19	2.81	2.12	0.06	0.18
25	Y7	SHUFU-5	Shufu body	Yuan	73.06	20.89	1.17	2.84	1.96	0.10	0.25
26	Y8	SHUFU-6	Shufu body	Yuan	72.71	21.43	1.25	3.07	1.57	0.18	0.20
27	Y9	Y-11	Blue-and-White body	Yuan	74.58	19.53	0.81	2.72	2.34	0.04	0.17
28	Y10	Y-8	Blue-and-White body	Yuan	74.91	19.47	0.16	3.03	2.39	0.90	0.08
29	Y11	Y-2	White Glaze body	Yuan	72.28	21.83	0.91	3.25	0.78	0.93	0.28
30	Y12	Y-5	Blue-and-White body	Yuan	71.95	20.75	0.84	2.73	2.76	0.15	0.16
31	M1	MJVR1	Coloured Glaze body	Ming	74.93	18.03	0.70	3.21	1.66	0.12	0.19
32	M2	SM10-1	Blue-and-White body	Ming	73.35	20.76	1.25	3.26	0.42	0.60	0.21
33	M3	MM-1	Blue-and-White body	Ming	75.31	18.20	0.73	4.28	1.75	0.65	0.16
34	M4	MM-2	Blue-and-White body	Ming	74.39	20.49	0.87	3.52	0.63	0.41	0.18
35	M5	MM-4	Blue-and-White body	Ming	76.03	19.17	1.04	3.26	0.14	0.53	0.26
36	M6	M-1′	Blue-and-White body	Ming	72.84	19.03	0.60	3.11	3.54	0.75	0.30
37	M7	M1	Blue-and-White body	Ming	73.58	20.05	0.90	2.87	2.01	0.53	0.14
38	M8	Q12	Blue-and-White body	Ming	74.05	19.97	0.79	3.13	1.16	0.13	0.16
39	M9	M-1	Blue-and-White body	Ming	73.66	21.24	0.59	3.12	0.60	0.12	0.15
40	M10	MM-6	Blue-and-White body	Ming	72.80	20.64	1.66	4.08	0.14	0.54	0.31
41	M11	MM-7	Blue-and-White body	Ming	74.63	18.83	1.25	3.18	1.15	1.02	0.26
42	M12	MM-8	Blue-and-White body	Ming	74.35	18.33	1.27	3.81	1.09	1.31	0.28
43	M13	M10	White Glaze body	Ming	74.53	19.97	0.84	3.18	0.60	0.45	0.15
44	M14	M-4	Blue-and-White body	Ming	73.38	18.49	1.24	3.30	1.00	1.21	0.18
45	M15	M-7	Blue-and-White body	Ming	74.29	19.41	0.88	3.80	1.42	0.27	0.20
46	M16	M5	Blue-and-White body	Ming	73.99	18.90	1.08	3.05	1.69	1.19	0.27
47	M17	MM-10	Blue-and-White body	Ming	74.75	18.53	0.77	4.02	1.89	0.66	0.23
48	M18	MM-9	Blue-and-White body	Ming	75.33	18.99	0.76	3.36	1.60	0.39	0.22
49	M19	MM-11	Blue-and-White body	Ming	73.48	20.20	1.02	3.79	1.86	0.42	0.20
50	M20	M-8	Blue-and-White body	Ming	73.59	19.61	0.87	3.46	1.95	0.46	0.17
51	M21	M-9	Blue-and-White body	Ming	75.62	19.12	0.99	3.55	0.86	0.24	0.18
52	M22	M3	Blue-and-White body	Ming	71.69	20.69	1.26	3.37	1.55	1.01	0.28
53	M23	MM-13	Blue-and-White body	Ming	72.42	21.69	0.74	3.51	0.95	1.02	0.18
54	Q_1	C-1	Blue-and-White body	Qing	68.07	25.82	0.83	3.04	1.54	0.36	0.11
55	Q_2	C-2	Blue-and-White body	Qing	65.76	28.57	0.84	3.22	0.83	0.50	0.12
56	Q_3	C11	Five Colours body	Qing	66.33	26.33	1.37	2.91	2.44	0.65	0.09
57	Q_4	C12	Blue-and-White body	Qing	68.59	24.08	1.15	3.13	2.35	0.71	0.30
58	Q_5	C14	Five Colours body	Qing	66.67	26.25	0.91	2.56	2.15	1.25	0.33
59	Q_6	C17	Doucai body	Qing	65.09	26.72	1.06	3.11	2.57	1.62	0.13
60	Q_7	C4	Blue-and-White body	Qing	70.22	22.97	0.81	3.49	1.18	0.68	0.11
61	Q_8	C13	Famille-rose body	Qing	67.78	26.25	0.84	3.28	1.12	0.71	0.16
62	Q_9	C15	Famille-rose body	Qing	66.27	27.42	0.77	3.07	1.29	1.36	0.13
63	Q_{10}	C22	Blue-and-White body	Qing	65.81	30.51	1.07	1.81	0.26	0.22	0.15
64	Q_{11}	C5	Blue-and-White body	Qing	70.38	24.10	0.82	3.33	0.69	0.66	0.15
65	Q_{12}	C20	White Glaze body	Qing	67.28	27.20	0.67	3.41	0.95	0.63	0.18
66	Q_{13}	C21	Blue-and-White body	Qing	68.93	24.25	0.84	2.38	1.87	0.74	0.20

Table 2. The elements of the symmetric correlation matrix.

	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	CaO	MgO
SiO_2	1.0000						
Al_2O_3	−0.9609	1.0000					
Fe_2O_3	−0.1362	0.0339	1.0000				
K_2O	0.0365	−0.0441	−0.0422	1.0000			
Na_2O	−0.2594	0.0882	−0.0781	−0.0769	1.0000		
CaO	−0.1583	0.0664	−0.0436	0.0480	−0.0629	1.0000	
MgO	0.3417	−0.3859	0.2593	−0.2584	−0.2361	0.1672	1.0000

compound are given by

$$\bar{x}_m = \frac{1}{N} \sum_{n=1}^{N} x_{nm}, \tag{1}$$

$$s_m^2 = \frac{1}{N-1} \sum_{n=1}^{N} (x_{nm} - \bar{x}_m)^2. \tag{2}$$

To avoid the concentration of any compound from having too much influence on the principal components, the data were auto-scaled to have zero mean and unit variance:

$$z_{nm} = \frac{x_{nm} - \bar{x}_m}{s_m}. \tag{3}$$

The principal components P are calculated [20] as linear combinations of the original variables (concentrations of compounds) such that the first principal component has the largest variance, the second principal component has the second largest variance and is orthogonal to the first and so on. This is expressed as

$$p_{nk} = \sum_{m=1}^{M} z_{nm} v_{mk}, \tag{4}$$

where p_{nk} is the k-th principal component for sample n and v_{mk} the m-th term of the k-th eigenvector of the $(M \times M)$ correlation matrix.

Results and Discussion

The principal component analysis was performed using the seven major and minor compounds (SiO_2, Al_2O_3, Fe_2O_3, K_2O, Na_2O, CaO and MgO) of the 66 samples. The first principal component is

$$\begin{aligned} p_{n1} = &+0.628\, z_{n1}(SiO_2) - 0.616\, z_{n2}(Al_2O_3) \\ &+ 0.017\, z_{n3}(Fe_2O_3) - 0.031\, z_{n4}(K_2O) \\ &- 0.243\, z_{n5}(Na_2O) - 0.047\, z_{n6}(CaO) \\ &+ 0.405\, z_{n7}(MgO). \end{aligned} \tag{5}$$

In this equation, variables with small coefficients (Fe_2O_3, K_2O and CaO) would have little effect on the value of p_{n1}. Therefore the first principal component is largely determined by SiO_2 and Al_2O_3, and to a certain extent by Na_2O and MgO. This can also be seen from Table 2 which gives the correlation amongst the various compounds. It is obvious that SiO_2 and Al_2O_3 are highly correlated whereas Fe_2O_3, K_2O and CaO are each weakly correlated with all the others except MgO. In contrast, all compounds have appreciable contributions (from −0.412 to −0.211 and from 0.194 to 0.554) to the second principal component p_{n2}, which is given by

$$\begin{aligned} p_{n2} = &-0.247\, z_{n1}(SiO_2) + 0.194\, z_{n2}(Al_2O_3) \\ &+ 0.554\, z_{n3}(Fe_2O_3) - 0.412\, z_{n4}(K_2O) \\ &- 0.211\, z_{n5}(Na_2O) + 0.308\, z_{n6}(CaO) \\ &+ 0.534\, z_{n7}(MgO). \end{aligned} \tag{6}$$

Figure 1 shows a plot of principal components p_1 and p_2 for the 66 pieces of Jingdezhen porcelains. Although there is appreciable overlap between porcelains from the Five Dynasties and the Song Dynasty and some overlap between Ming and Song and also between Ming and Yuan, it is obviously still possible to distinguish with confidence Ming porcelains from the Five Dynasties and Qing porcelains or to distinghuish Yuan porcelains from porcelains of the Five Dynasties, the Song and Qing Dynasties. Qing porcelains are well separated from all the others because they have relatively much higher alumina and much lower silica, as indicated below.

From Table 3, owing to minimal overlap in the values of the first principal components for the various dynasties, p_{n1} should be the best measure of time. From (5), the two largest coefficients (+0.628 and −0.616) would produce the largest effect on the values of p_{n1}. Since the coefficient is positive (+0.628) for SiO_2 and negative (−0.616) for Al_2O_3, the percentage of silica decreases and that of alumina increases as a

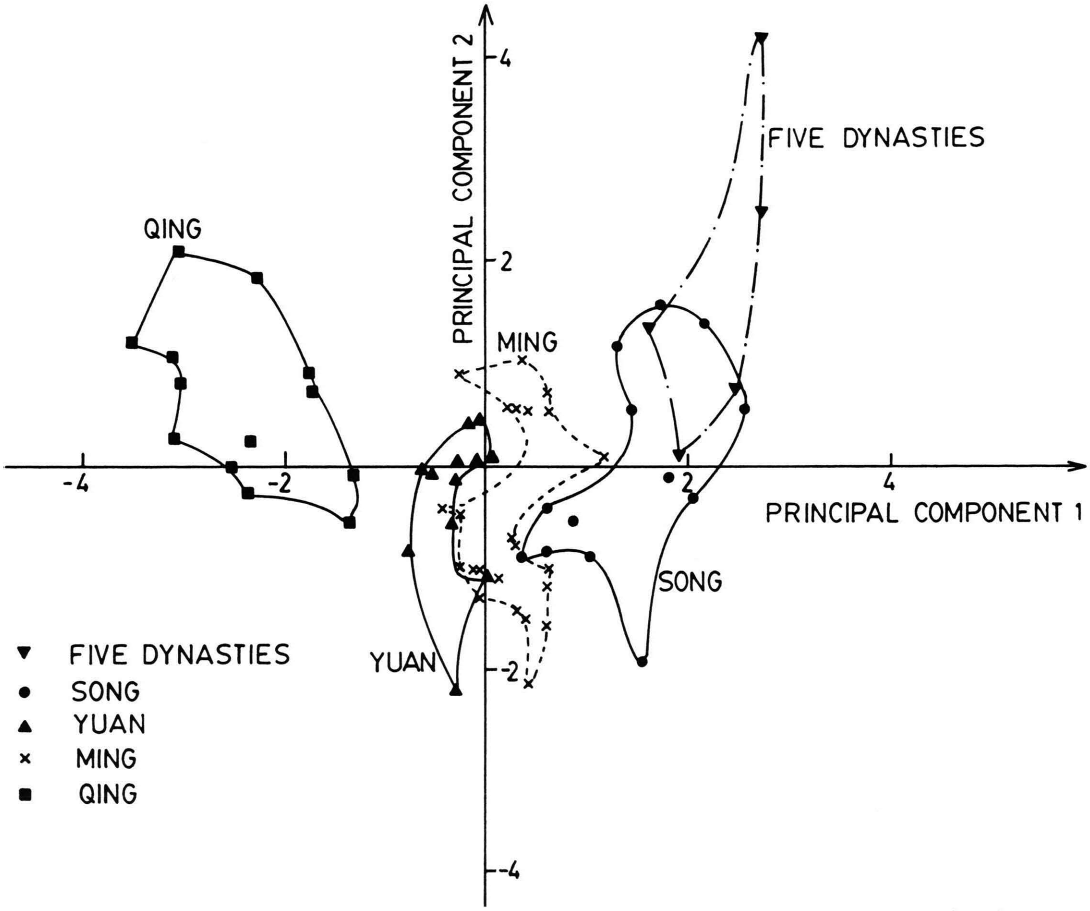

Fig. 1. Plot of the first two principal components given by (5) and (6) of Jingdezhen porcelains, using the concentrations of 7 major and minor compounds (SiO_2, Al_2O_3, Fe_2O_3, K_2O, Na_2O, CaO and MgO) from the body of the porcelain.

Table 3. The extent of the values of principal components 1 and 2 for the various periods.

Dynasties	The first principal component p_{n1}		The second principal component p_{n2}	
	from	to	from	to
Five Dynasties	+0.648	+2.717	+0.02	+4.233
Song	+0.341	+2.680	−1.899	+1.561
Yuan	−0.833	+0.113	−2.316	+0.484
Ming	−0.485	+1.267	−2.187	+1.007
Qing	−1.288	−3.545	−0.653	+2.150

function of time [4], with the exception of the Yuan and Ming dynasties, where this trend is reversed.

As is well-known, porcelains are made from a mixture of China-stone and China-clay (kaolin), the latter containing a much larger percentage (~40%) of alumina than the former (~18%). Therefore, from the results of our analysis, we conclude that originally during the Five Dynasties and also to a certain extent during the Song Dynasty, porcelains were made of one kind of raw material, namely, China-stone. By the time of the Yuan and Ming dynasties, both types of raw materials (China-stone and kaolin) were used. The initial addition of kaolin to China-stone during the Yuan Dynasty seems to be rather liberal as the subsequent Ming Dynasty had the proportion of kaolin cut down. However, during the Qing Dynasty, an unusually large proportion of kaolin was again used.

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