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Compositional Analysis of Shang – Zhou Pottery from the Longhucun Site, Chengdu, Sichuan, China

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Abstract: The Longhucun site in Chengdu was a Shang – Zhou pottery workshop. XRF analysis of 44 pottery samples investigated chemical composition, raw materials, and diachronic variation. The pottery is silica-rich (61.81 wt.% SiO₂), moderately aluminous (21.33 wt.% Al₂O₃), and iron-rich (7.81 wt.% Fe₂O₃). Trace element coefficients of variation (Zr, Rb, Zn, Cr) are below 20%, indicating consistent raw material selection. All three phases belong to a high-silica, moderate-alumina system, with no fundamental change, but show a trajectory of relative dispersion – concentration – renewed dispersion, with increased variability in Phase III. Anomalous P, Mn, and S concentrations suggest distinctive production techniques and post-depositional contamination. Comparison with Sanxingdui and Jinsha indicates a pattern of raw-material differentiation and shared technological origin in Chengdu Plain pottery production.

1. Introduction

The Longhucun site is located on the boundary between Xindu and Qingbaijiang districts of Chengdu, within the middle reaches of the Tuo River drainage system (Qingbaijiang – Pi River basin). Archaeological analysis indicates that Layers 6 – 9 and the features sealed beneath them date to the Shang – Zhou period. Three radiocarbon dates were obtained: H3, sealed beneath Layer 9 and cutting into sterile subsoil, dates to 3120 ± 30 BP; Y2, sealed beneath Layer 9 and cutting into sterile subsoil, dates to 2900 ± 30 BP; and H307, sealed beneath Layer 2 and cutting through Layer 9 into sterile subsoil, dates to 2470 ± 30 BP (Fig. 1). On the basis of stratigraphy, typology, and radiocarbon dating, we divide the Shang – Zhou remains at the Longhucun site into three phases: Phase I dates from the late Shang to the early Western Zhou; Phase II from the early to middle Western Zhou; and Phase III spans from the middle – late Western Zhou period to the middle Spring and Autumn period [1].

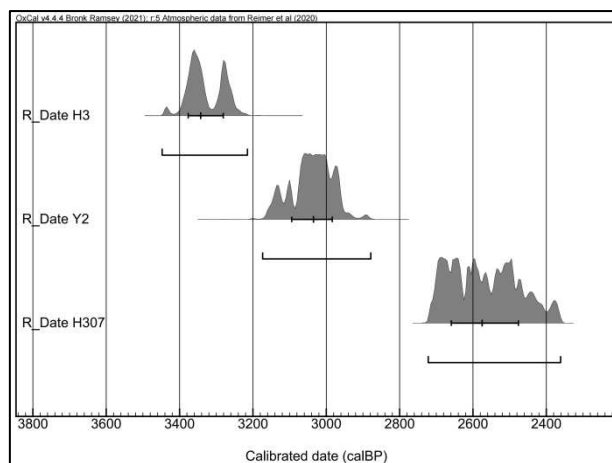


Fig. 1. Bayesian chronological model of radiocarbon dates from the Longhucun site.

The Longhucun site is one of the most important pottery-production workshops in the Chengdu Plain during the Shang – Zhou period. Excavations have revealed 19 pottery kilns, the largest kiln cluster in the Chengdu Plain apart from the Jinsha site, along with hundreds of features including ash pits, ash ditches, and tombs. The site also yielded abundant pottery, as well as jade and stone objects such as stone yazhang blades, jade axes, and jade chisels (Fig. 2). Notably, a pottery seal interpreted as a marker of potters' identity or the workshop's

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specialized character was recovered. These discoveries indicate that Longhucun was not merely an ordinary settlement with household pottery production, but a specialized workshop site where pottery was produced in an organized manner. Compositional analysis has long been central to investigating pottery provenance and raw material procurement [2,3]. Integrated macro-, micro-, and chemical analyses are essential for reconstructing production technology [4]. Petrographic studies of Chengdu Plain ceramics have suggested long-term continuity in production traditions [5]. However, systematic compositional analysis of pottery from a specialized workshop site such as Longhucun has not yet been conducted. This study therefore conducts XRF analysis of 44 pottery samples from Longhucun, aiming to characterize the chemical composition, raw material sources, and diachronic evolution of pottery production at this key workshop site.

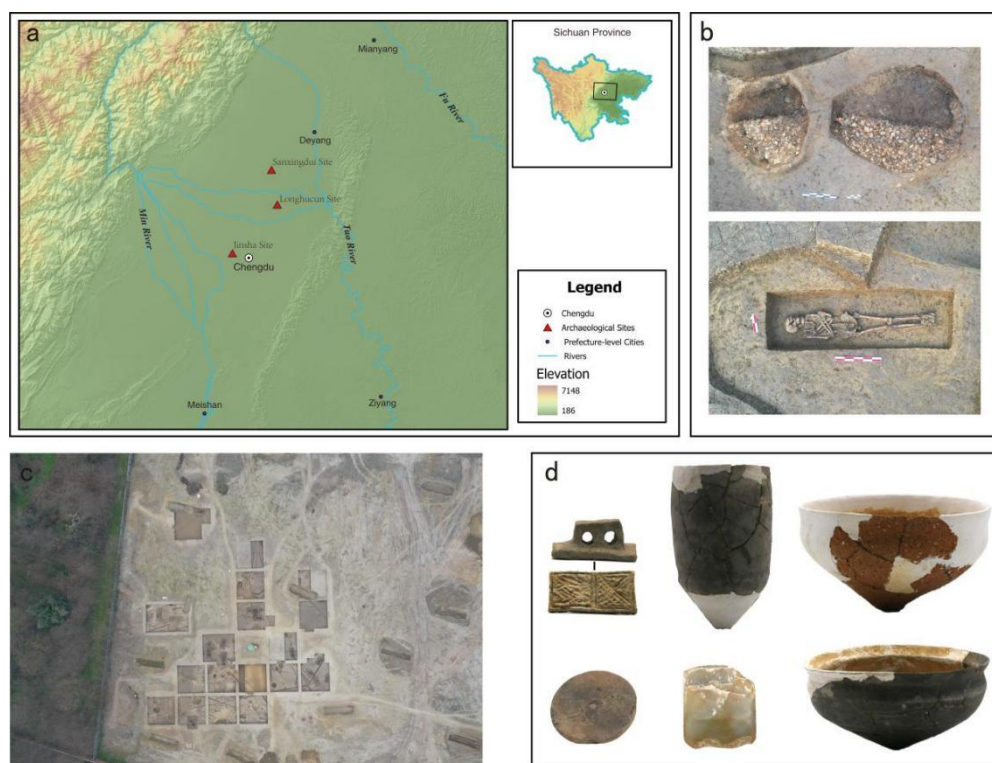


Fig. 2. Location, excavation overview, archaeological features, and representative artifacts of the Longhucun site. (a) Location of the Longhucun site. (b) Selected archaeological features at the Longhucun site. (c) Aerial view of the excavation area. (d) Representative artifacts unearthed from the site.

2. Methods

2. 1. Sample information

A total of 44 pottery samples recovered from Shang – Zhou archaeological features at the Longhucun site were selected for analysis. The assemblage consists mainly of sandy ware, with a smaller proportion of fine clay ware. The surface colors of the samples are predominantly dark brown, followed by reddish brown, whereas the cores are mainly reddish brown or yellowish brown. Identifiable vessel forms include high-necked jars, curved-bellied jars, small flat-bottomed jars, spindle whorls, cylindrical vessels, pointed-bottom cups, and pointed-bottom saucers (Table 1 and Fig. 3). Sample selection and classification followed standard procedures for archaeological ceramic analysis [4,6].

Table 1. Information on the analyzed pottery samples from the Longhucun site.

Sample	Archaeological number	Phase	Vessel form	Ware
001	H238-2	Phase I	Curved-bellied jar	Sandy ware

002	Y1-4	Phase III	Foot ring	Sandy ware
003	H260-1	Phase I	Spindle whorl	Clay ware
004	H142-1	Phase I	Body sherd	Sandy + clay ware
005	Y1-3	Phase III	Pointed-bottom jar	Sandy ware
006	Y18-2	Phase III	Cylindrical kiln furniture	Sandy ware
007	TN02E02⑨-1	Phase II	Pointed-bottom saucer	Sandy ware
008	Y1-5	Phase III	Low-necked jar	Sandy ware
009	H296-1	Phase I	Pottery bottle	Sandy ware
010	H256-1	Phase I	High-necked jar	Sandy ware
011	H16③-2	Phase I	Vessel lid	Sandy ware
012	H160-3	Phase I	tall ring foot	Sandy ware
013	D4-1	Phase I	Dou stem	Sandy ware
014	H160-1	Phase I	Body sherd	Sandy ware
015	H160-2	Phase I	Flat base	Sandy + clay ware
016	D4-3	Phase I	High-necked jar	Sandy ware
017	H93-1	Phase I	Cord-marked restricted-mouth jar	Sandy ware
018	H238-1	Phase I	High-necked jar	Sandy ware
019	D4-4	Phase I	Pointed-bottom saucer	Clay ware
020	H54②-1	Phase I	Restricted-mouth jar	Sandy ware
021	H16③-1	Phase I	Small flat-bottomed jar	Sandy ware
022	Y10-1	Phase III	Thick-lipped urn	Sandy ware
023	Y1-6	Phase III	Flat base	Sandy ware
024	H91-1	Phase I	Body sherd	Sandy ware
025	H91-3	Phase I	Cylindrical kiln furniture	Sandy ware
026	H91-2	Phase I	Everted-rim jar	Sandy ware
027	Y18-1	Phase III	Low-necked wide-shouldered jar	Sandy ware
028	H259-1	Phase I	Pottery flask	Clay ware
029	H239-1	Phase I	Flared-rim rounded-shoulder jar	Sandy ware
030	Y1-1	Phase III	Pointed-bottom cup	Clay ware
031	Y1-2	Phase III	Pointed-bottom cup	Sandy ware
032	Y4-1	Phase I	Low-necked jar	Sandy ware
033	D12-1	Phase I	Restricted-mouth angular-shouldered jar	Sandy ware
034	TN02E03⑨-1	Phase II	Pottery spindle whorl	Clay ware
035	D4-2	Phase I	Dou stem	Clay ware
036	H307①-1	Phase III	Cord-marked jar	Sandy ware
037	TN07E05⑨-1	Phase II	Body sherd	Sandy + clay ware
038	TN05E02⑨-1	Phase II	Body sherd	Sandy + clay ware
039	TN02E03⑨-2	Phase II	Foot ring	Sandy ware
040	H307②-1	Phase III	Pendant-rim urn	Sandy ware
041	TN02E02⑨-2	Phase II	Everted-rim jar	Sandy ware
042	TN08E03⑨-2	Phase II	Cylindrical kiln furniture	Sandy ware
043	TN06E07⑨-1	Phase II	Vessel base	Sandy ware
044	TN08E03⑨-1	Phase II	Pointed-bottom cup	Clay ware

Note: "Sandy + clay ware" indicates that the sample contains both sandy ware and clay ware components. Based on our previous excavations of archaeological materials, many pottery vessels in Shang – Zhou remains of the Chengdu Plain were formed by combining coil-building of sandy ware with slab-building of clay ware.



Fig. 3. Photographs of selected samples.

2.2. Instrumentation and analytical conditions

Stereomicroscopic observations were conducted using a ZEISS SteREO Discovery.V20 research-grade fully motorized stereomicroscope (ZEISS, Germany) to examine the microstructures and inclusions of pottery cross-sections. The instrument has a zoom ratio of 20:1, a continuous zoom range of 0.75 $\times$ –15 $\times$, and a total magnification of 4.7 $\times$ –1312.5 $\times$. It offers a maximum resolution of 1000 lp/mm (line pairs per millimeter), a working distance of 10–253 mm, and a focusing accuracy of 350 μ m. Motorized adjustment of magnification, focus, and illumination is achieved via the SYCOP touch panel. Petrographic observation of ceramic cross-sections follows standard procedures for identifying inclusions and voids [7].

X-ray fluorescence (XRF) analysis was performed using a Bruker M4 Tornado micro-XRF spectrometer (Bruker Nano GmbH, Germany). The instrument was equipped with a Rh microfocus X-ray tube operated at 50 kV and 299 μ A, with an elemental detection range of Na to U. Measurements were conducted under vacuum (approximately 19.9 mbar). The instrument employs polycapillary X-ray lens focusing, achieving a minimum analytical spot size of 20 μ m. It supports point analysis, line scanning, and mapping, and can be used to characterize the elemental composition and distribution in pottery samples. XRF has been shown to provide reliable compositional data for ceramic provenance studies [8,9], and recent applications have successfully distinguished production centers using trace elements such as Ni, Cr, Rb, Sr, and Zr [10]. Comparative studies of quantitative and qualitative EDXRF analyses have further confirmed the reliability of XRF-based provenance discrimination [11].

A standardless quantification model was applied in this study. Although the absolute accuracy of standardless XRF analysis is limited for light and trace elements in complex silicate matrices, all samples were measured under identical conditions and normalized in the same manner, ensuring that systematic bias remained consistent across the entire dataset and that internal comparisons remained valid. Comparative studies have demonstrated that XRF data can achieve similar grouping and resolution levels to NAA data [9,12,13].

Although the instrument has a minimum analytical spot size of 20 μ m, the data in this study were derived from area mapping rather than single-point analysis. The cross-section of each sample was mapped over a sufficiently large area to average the inhomogeneous grains and matrix structure of the ceramic body. Preliminary tests showed that differences among point, line, and area measurements were less than 1%, confirming that the mapped area is representative and reflects the bulk composition. Single-point analysis was not used because the content of low-concentration elements within an individual spot may fall below the detection limit. This approach is consistent with recommended practices for XRF analysis of heterogeneous archaeological ceramics [6].

3. Results

3.1. Microscopic observation of pottery from the Longhucun site

A total of 44 pottery samples from the Longhucun site were examined in cross-section under

a stereomicroscope (Fig. 4). In accordance with conventional archaeological criteria, the samples were classified into three categories: sandy ware ($n = 34$, 77.3%), clay ware ($n = 6$, 13.6%), and mixed sandy-clay ware ($n = 4$, 9.1%). In cross-sections of sandy ware, abundant grains were observed. These grains varied in color, including black, milky white, transparent, reddish brown, pale yellow, grayish white, greenish yellow, grayish brown, and dark brown. Grain sizes varied widely, ranging from approximately 0.01 to 1.83 mm, with most grains measuring between 0.20 and 0.60 mm. Grain morphologies were diverse, including rounded, irregular, elongated, sub-rectangular, and triangular forms. The grains were mostly randomly distributed, with no evident preferred orientation. In clay ware, grains were markedly fewer and generally finer, mostly between 0.001 and 0.05 mm. In mixed ware, the sandy and clay portions differed significantly in grain abundance and size, and in some samples the boundary between them was relatively distinct. Regarding voids, sandy ware commonly contained small rounded pores and elongated fissures, generally 0.01–0.20 mm in size, with fissures up to 1.40 mm long; clay ware had fewer and smaller voids, mostly 0.001–0.05 mm. Overall, the grains of various colors in the sandy ware were poorly sorted, morphologically diverse, and randomly distributed.

Color layering in cross-section was common in about half of the samples. From the outer surface to the inner wall, multi-colored sequences such as dark brown → yellowish brown → grayish brown → gray were frequently observed. The layers varied in thickness, ranging from only 0.01–0.03 mm to several millimeters. Notably, in all color-layered samples, the grain types, sizes, and quantities within different colored layers showed no significant differences, indicating that the color layering was mainly related to firing atmosphere, temperature differences, or redox conditions during use, rather than to the inclusions in the ceramic body. In addition, some samples exhibited notable peculiarities in the characteristics of inclusions in the ceramic body. Samples 009, 024, and 036 showed relatively high proportions of reddish-brown grains. In Sample 009, these grains ranged from 0.23 to 1.60 mm in size, whereas transparent grains were considerably less abundant. The gray ware of Sample 025, 026, and 029 contained abundant extremely fine white grains (0.01–0.05 mm), which may reflect differences in raw material characteristics or tempering practices. Sample 024 exhibited conspicuous elongated fissures at the edges of the cross-section, indicating a relatively friable ceramic body. In Sample 017, fine grains were still visible within the extremely thin black surface layer (0.05–0.08 mm thick). These differences indicate that the inhabitants of the Longhucun site applied a certain degree of differentiated treatment in raw material selection or temper proportions, reflecting a differentiation in raw material processing and pottery function within the ceramic production process. Similar petrographic observations have been reported for other Chengdu Plain ceramics [5].

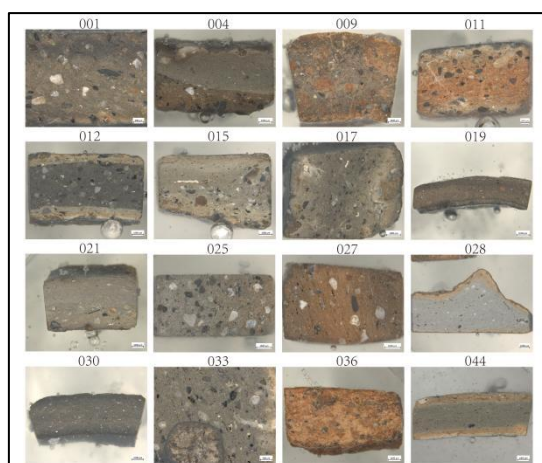


Fig. 4. Photomicrographs of selected samples.

3.2. Composition of pottery from the Longhucun site

Prior to analysis, all samples were ultrasonically cleaned to remove surface deposits and potential contaminants. Each sample was then embedded in epoxy resin and ground flat so that the analytical surface was a fresh cross-section, ensuring that the measured composition reflects the ceramic body rather than an altered surface layer. The samples were cleaned again in an

ultrasonic cleaner. After drying, the cross-sections of the pottery samples were measured using an M4 Tornado XRF spectrometer with standardless quantitative analysis. To facilitate comparative analysis, all major, minor, and trace elements are expressed as oxides. The XRF data were normalized so that the sum of the 18 detected oxides was equal to 100 wt.%. Major and minor oxides are reported in wt.%, and trace element oxides in $\mu\text{g/g}$ (1 wt.% = 10,000 $\mu\text{g/g}$). Because trace element oxides were included in the same normalization procedure, their values represent relative concentrations within the normalized bulk composition rather than independently quantified absolute concentrations. The mass contribution of the trace elements is very small; consequently, the sum of the major and minor oxides alone is slightly less than 100 wt.%. Major and minor oxides were rounded to two decimal places and trace elements to whole numbers, which may result in minor discrepancies in the sums shown in the tables¹. The XRF data are presented in Tables 2 and 3.

Table 2. Results of major and minor element analysis (wt.%).

Sample	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	P ₂ O ₅	Na ₂ O	MgO
001	20.97	61.01	2.73	1.73	1.06	0.04	7.61	3.46	0.82	0.41
002	20.44	63.87	2.99	1.29	1.13	0.06	7.17	0.15	1.42	1.3
003	24.37	57.63	3.8	1.51	1.22	0.43	6.73	2.37	0.49	1.27
004	21.52	63.77	2.85	1.51	1.14	0.03	6.05	1.69	0.75	0.53
005	22.1	59.78	2.81	1.66	1.04	0.16	8.39	1.65	0.87	1.31
006	18.95	65.11	3.01	1.53	0.89	0.05	7.41	0.29	1.43	1.19
007	22.56	59.53	2.7	1.62	0.98	0.05	8.77	1.45	1.39	0.8
008	24.08	56.62	2.03	1.63	1.17	0.2	11.07	0.86	1.39	0.72
009	21.22	58.04	2.61	1.44	0.99	0.89	12.13	0.1	0.62	1.73
010	19.19	64.53	2.26	1.94	0.98	0.05	8.17	0.64	1.28	0.81
011	22.34	61.99	2.86	1.32	1	0.08	7.73	1.35	0.63	0.53
012	21.24	60.54	2.72	2.14	1.1	0.07	6.1	3.86	1.3	0.79
013	22.3	58.21	2.63	2.01	1.08	0.07	9.81	1.12	0.99	1.57
014	21.59	60.5	2.73	1.48	1.01	0.08	8.83	1.85	1.06	0.69
015	20.23	62.97	2.81	1.59	1.01	0.05	6.09	3.28	1.15	0.68
016	22.22	57.51	2.85	2.13	1.03	0.08	9.64	2.64	0.58	1.16
017	20.42	63.51	2.74	1.38	1.05	0.02	6.69	2.53	1	0.51
018	19.3	63.9	2.56	1.78	0.93	0.04	7.52	1.9	1.15	0.77
019	20.06	65.56	2.9	1.55	1.16	0.07	5.28	2.47	0.11	0.69
020	19.38	63.66	2.46	1.91	1.03	0.04	7.61	2.07	1.01	0.64
021	21.73	62.59	3.04	1.77	1.16	0.04	5.05	2.99	0.74	0.74
022	19.31	63.81	3.31	1.91	0.89	0.05	7.7	0.41	1.19	1.07
023	21.26	64.93	2.9	1.08	1.07	0.05	6.43	0.83	0.78	0.46
024	23.8	58.14	3.61	1.02	0.98	0.4	9.13	0.52	1.06	1.16
025	18.4	65.94	2.92	1.33	0.87	0.08	7.94	0.21	1.03	1.14
026	18.96	62.63	2.75	1.93	1.07	0.04	7.17	3.44	1.3	0.56
027	20.87	63.14	2.79	1.09	1.01	0.09	8.6	0.34	0.66	1.21
028	24.2	63.15	2.92	0.92	1.25	0.02	5.68	0.49	0.35	0.89
029	20.32	62.77	2.48	1.93	1.01	0.09	6.96	2.87	1.02	0.42
030	24.39	55.34	3.3	1.58	1.16	0.22	9.9	1.78	0.51	1.57
031	22.14	59.06	3.26	1.7	1.08	0.16	8.43	1.67	0.79	1.54
032	23.37	61.78	2.11	1.35	1.13	0.03	7.29	0.73	1.4	0.65
033	19.64	60.52	2.68	1.9	1.03	0.78	9.48	1.8	1.03	0.92
034	22.63	60.9	2.75	1.19	1.11	0.02	9.62	0.71	0.05	0.77
035	21.78	58.74	3.25	1.5	1.01	0.1	9.59	1.52	0.7	1.61
036	22.42	60.32	3.06	1.4	1.06	0.4	9.27	0.29	0.38	1.16
037	23.84	60.17	3.05	1.48	1.33	0.03	6.12	2.59	0.58	0.63

¹ Since all samples were normalized in the same way, this treatment does not affect the internal comparability of the dataset, although the values should not be interpreted as absolute concentrations.

038	21.61	64.50	2.46	0.93	1.12	0.02	6.94	0.33	1.00	0.91
039	20.38	62.04	3.08	1.95	0.97	0.09	7.83	1.37	1.00	1.15
040	19.97	65.46	2.3	1.56	0.93	0.04	7.16	0.62	1.21	0.61
041	19.02	64.78	2.17	1.76	0.86	0.05	7.71	1.26	1.21	1.02
042	21.09	65.05	2.79	1.4	1.02	0.05	6.6	0.17	0.61	0.99
043	20.31	63.58	2.27	1.46	1	0.03	8.56	0.47	1.1	1.02
044	22.4	61.99	2.98	1.56	1.27	0.03	5.84	2.76	0.45	0.57

Table 3. Results of trace element analysis (µg/g).

Sample	Cr ₂ O ₃	NiO	ZnO	Rb ₂ O	SrO	SO ₃	CoO	ZrO ₂
001	184	69	148	170	435	15	284	285
002	184	52	165	186	237	464	249	305
003	244	93	170	260	321	180	245	323
004	198	35	144	193	336	172	216	372
005	220	98	207	185	312	595	318	317
006	145	40	166	182	214	86	262	299
007	188	99	169	164	295	16	303	317
008	294	111	212	120	346	522	426	303
009	213	199	196	199	303	277	486	361
010	185	66	154	125	363	53	287	259
011	176	92	204	175	267	200	275	312
012	198	63	166	162	471	0	219	277
013	270	97	223	173	353	207	350	300
014	192	50	188	170	327	124	310	340
015	153	48	152	167	392	9	236	353
016	242	77	207	204	392	0	336	256
017	180	54	128	170	296	0	245	368
018	181	53	143	151	375	0	287	287
019	181	68	210	178	311	0	208	404
020	185	42	144	142	441	115	286	337
021	191	58	139	197	371	0	177	308
022	220	37	162	159	302	2197	273	304
023	194	44	159	175	241	828	230	328
024	197	72	180	252	278	194	334	313
025	131	33	157	189	196	185	281	304
026	184	45	121	171	450	0	255	318
027	147	58	222	176	207	482	303	320
028	209	61	165	177	145	39	211	323
029	201	61	127	143	385	0	249	264
030	328	126	245	202	252	685	365	282
031	259	89	209	188	298	240	298	282
032	201	53	159	109	259	226	249	304
033	190	122	205	176	385	400	371	319
034	202	49	171	203	171	964	311	355
035	223	90	200	211	280	328	348	314
036	195	89	220	228	286	543	334	448
037	239	71	145	193	331	269	195	354
038	186	50	170	156	169	494	226	370
039	208	81	188	188	237	88	256	237
040	186	48	148	146	283	122	238	298
041	187	61	154	139	310	138	245	264
042	172	65	168	197	194	907	229	310
043	173	49	166	175	264	517	271	291
044	202	53	153	183	324	0	187	330

3.3. Analysis

3.3.1. General characteristics of chemical composition

A total of 18 oxides were detected in the 44 pottery samples from the Longhucun site. Of these, 10 are major and minor elements, including Al_2O_3 , SiO_2 , K_2O , and Fe_2O_3 , while 8 are trace elements, including Cr_2O_3 , NiO , and ZnO . To investigate relationships among chemical components and explore possible associations related to raw materials, R-mode cluster analysis was performed on the 18 oxides using Pearson correlation coefficients and the average linkage method. The choice of elements and statistical methods can significantly influence the identification of chemical groups [14]. Nevertheless, statistical clustering of XRF data has been widely applied to ceramic provenance studies, often combined with mineralogical and thermal analyses for validation [15]. Because the data were normalized to a constant sum (100 wt.%), they are compositional and subject to the closure effect, which may generate artificial negative correlations among components. The R-mode cluster analysis is therefore used here as an exploratory tool for identifying co-occurrence patterns rather than as a strict statistical test of geochemical relationships. Positive co-occurrence groups are less affected by closure and are interpreted as reflecting mineralogical associations. (Fig. 5 ;Supplementary Fig. S1).

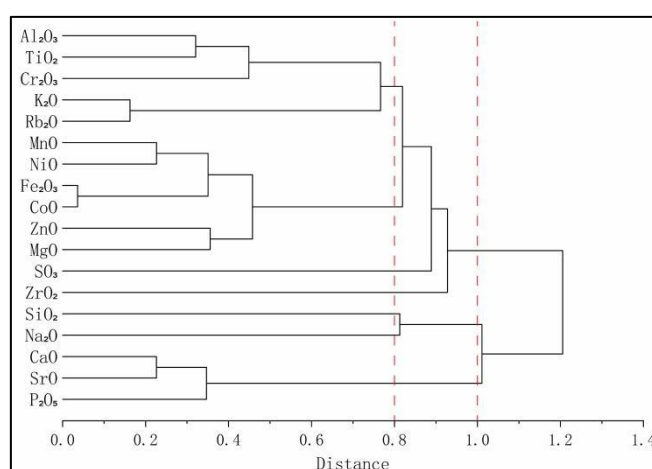


Fig. 5. R-mode cluster analysis dendrogram of the chemical composition of pottery from the Longhucun site.

To evaluate whether the observed clustering patterns were affected by the closure effect, the data were additionally transformed using the centered log-ratio (CLR) method [16]. Prior to transformation, zero values were replaced by 0.65 times the minimum non-zero value of the corresponding element, following standard practice in compositional data analysis [17]. All oxides were then re-normalized to 100 wt.%, and the CLR transformation was applied using the geometric mean of all components as the divisor. A correlation matrix was calculated on the CLR coordinates, and hierarchical clustering with average linkage was performed [18]. The resulting dendrogram was compared with that obtained from the raw percentage data.

When the dendrogram is cut at a distance threshold of approximately 0.8, the chemical components showing significant positive correlations can be divided into three distinct co-occurring groups (clusters). The first is an aluminosilicate/feldspathic assemblage (Al_2O_3 , TiO_2 , Cr_2O_3 , K_2O , Rb_2O), which exhibits a very strong affinity and represents the primary clay minerals and associated impurities of the pottery raw materials. The second is a mafic/heavy mineral assemblage (MnO , NiO , Fe_2O_3 , CoO , ZnO , MgO), reflecting the co-occurrence relationships of heavy mineral components such as sand grains and Fe–Mn nodules in the clay. The third is a calcium phosphate/calcareous assemblage (CaO , SrO , P_2O_5). Because Ca and Sr undergo isomorphous substitution, and P is often associated with bone or phosphate minerals, this assemblage indicates the possible addition of calcareous raw materials during production or enrichment in specific burial environments. Correspondingly, SiO_2 , Na_2O , ZrO_2 , and SO_3 did not show significant clustering with other components and displayed a highly independent character. Among these, SiO_2 and Na_2O had clustering distances greater than 1.0 from other components and showed pronounced negative correlations. This is partly attributed to the closure effect produced by the dominant component SiO_2 , which inevitably induces negative correlations with other components in a constant-sum dataset. The dilution effect may also contribute. Therefore,

these negative correlations should be interpreted with caution. ZrO_2 , as an indicator of the stable heavy mineral zircon, and SO_3 , which may represent specific local contamination or kiln atmosphere, both exhibit independent mobilization or addition mechanisms.

The CLR-based clustering largely reproduced the raw-data groupings. The calcium phosphate/calcareous assemblage (CaO , SrO , P_2O_5) and the mafic/heavy mineral assemblage (MnO , NiO , Fe_2O_3 , CoO , MgO) remained robust. The aluminosilicate/feldspathic assemblage (Al_2O_3 , TiO_2 , Cr_2O_3 , K_2O , Rb_2O) also remained largely intact. Minor differences were observed: SO_3 shifted into the mafic/heavy mineral group, and ZnO shifted toward the aluminosilicate group. These shifts likely reflect the removal of the closure effect, as the strong dilution effect of the dominant component SiO_2 was no longer constraining the correlations. Na_2O , SiO_2 , and ZrO_2 remained independent.

This consistency suggests that the three principal co-occurrence groups identified in the raw-data analysis are unlikely to be solely caused by the closure effect and may reflect underlying mineralogical associations. In summary, R-mode cluster analysis effectively disentangles the complex mixed signals of the pottery, reveals three distinct mineral-genetic assemblages and two independent addition/contamination sources, and provides an important geochemical basis for subsequent discussion of the raw material recipes, production technology, and provenance of this batch of pottery. The CLR-based dendrogram is provided in the Supplementary Material. Based on the analytical data, the means, standard deviations, and coefficients of variation of the major and minor element compositions are presented in Table 4, and those of the trace element compositions are presented in Table 5.

Table 4. Means (wt.%), standard deviations, and coefficients of variation (%) of major and minor element compositions of pottery from the Longhucun site.

	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO	Fe_2O_3	P_2O_5	Na_2O	MgO
Mean	21.33	61.81	2.80	1.56	1.05	0.12	7.81	1.50	0.90	0.93
SD	1.64	2.71	0.37	0.31	0.10	0.19	1.54	1.07	0.35	0.35
CV	7.68	4.38	13.12	19.59	9.90	149.18	19.67	71.32	39.38	38.00

Table 5. Means ($\mu\text{g/g}$), standard deviations, and coefficients of variation (%) of trace element compositions of pottery from the Longhucun site.

	Cr_2O_3	NiO	ZnO	Rb_2O	SrO	SO_3	CoO	ZrO_2
Mean	200.86	69.80	173.39	177.48	304.66	292.75	278.73	316.25
SD	36.95	30.58	29.65	29.80	77.66	393.78	62.27	39.84
CV	18.39	43.82	17.10	16.79	25.49	134.51	22.34	12.60

The chemical compositions of the 44 pottery samples from the Longhucun site exhibit the following characteristics. (1) Overall, the pottery assemblage displays a chemical profile characterized by high silica (mean $\text{SiO}_2 = 61.81\%$), moderate alumina (mean $\text{Al}_2\text{O}_3 = 21.33\%$), and high iron (mean $\text{Fe}_2\text{O}_3 = 7.81\%$). Together, SiO_2 and Al_2O_3 account for approximately 83.14% of the total mass of the pottery and constitute the principal components of the ceramic body. (2) Among the major elements, SiO_2 and Al_2O_3 show relatively small variations (CV = 4.38% and 7.68%, respectively, both < 8%). Among the trace elements, the CVs of ZrO_2 , Rb_2O , ZnO , and Cr_2O_3 are all below 20% (12.60%, 16.79%, 17.10%, and 18.39%, respectively), suggesting relatively consistent raw material characteristics. (3) The coefficients of variation for P_2O_5 , MnO , and SO_3 are extremely high (CV = 71.32%, 149.18%, and 134.51%, respectively), indicating substantial variability among samples. These anomalies may be related to specific production practices or post-depositional contamination and require further investigation.

3.3.2. Diachronic analysis

On the basis of archaeological stratigraphy and typology, combined with radiocarbon dates, we divided the Shang–Zhou remains at the Longhucun site into three phases. To investigate diachronic variations in the chemical composition of pottery from the Longhucun site, we conducted a diachronic analysis of the 44 samples examined in this study. Phase I includes samples 001, 003, 004, 009, 010, 011, 012, 013, 014, 015, 016, 017, 018, 019, 020, 021, 024, 025,

026, 028, 029, 032, 033, and 035; Phase II includes samples 007, 034, 037, 038, 039, 041, 042, 043, and 044; and Phase III includes samples 002, 005, 006, 008, 022, 023, 027, 030, 031, 036, and 040. The means, standard deviations, and coefficients of variation of the major, minor, and trace element compositions of the pottery from each phase are presented in Tables 6 and 7.

Table 6. Means (wt.%), standard deviations (SD), and coefficients of variation (CV, %) of major and minor element compositions of pottery from each phase at the Longhucun site.

Phase	Statistic	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	P ₂ O ₅	Na ₂ O	MgO
Phase I	Mean	21.19	61.65	2.80	1.63	1.05	0.15	7.68	1.91	0.90	0.87
Phase I	SD	1.68	2.55	0.37	0.33	0.09	0.24	1.69	1.11	0.32	0.38
Phase I	CV	7.92	4.14	13.12	20.05	8.42	156.00	22.06	57.95	36.03	43.50
Phase II	Mean	21.54	62.50	2.69	1.48	1.07	0.04	7.55	1.23	0.82	0.87
Phase II	SD	1.49	2.07	0.33	0.30	0.15	0.02	1.28	0.94	0.43	0.19
Phase II	CV	6.90	3.31	12.30	20.21	14.02	53.63	16.97	76.00	51.88	22.24
Phase III	Mean	21.45	61.59	2.89	1.49	1.04	0.13	8.32	0.81	0.97	1.10
Phase III	SD	1.78	3.55	0.40	0.26	0.10	0.11	1.36	0.62	0.38	0.36
Phase III	CV	8.32	5.77	14.02	17.20	9.64	81.85	16.35	76.10	39.14	32.89

Table 7. Means (µg/g), standard deviations (SD), and coefficients of variation (CV, %) of trace element compositions of pottery from each phase at the Longhucun site.

Phase	Statistic	Cr ₂ O ₃	NiO	ZnO	Rb ₂ O	SrO	SO ₃	CoO	ZrO ₂
Phase I	Mean	196	71	168	178	339	114	281	317
Phase I	SD	28.69	34.65	29.86	34.00	79.01	120.89	66.81	37.07
Phase I	CV	14.62	48.89	17.78	19.14	23.32	106.51	23.77	11.70
Phase II	Mean	195	64	165	177	255	377	247	314
Phase II	SD	20.64	17.10	12.65	21.05	64.94	368.02	43.25	44.24
Phase II	CV	10.57	26.63	7.67	11.85	25.47	97.62	17.51	14.08
Phase III	Mean	216	72	192	177	271	615	300	317
Phase III	SD	57.58	31.46	32.77	28.38	43.73	571.95	59.25	45.75
Phase III	CV	26.70	43.69	17.04	16.04	16.15	93.01	19.78	14.44

3.3.2.1. Diachronic analysis of major components

Across different phases, SiO₂ and Al₂O₃ remained the major components, and their coefficients of variation (CVs) were the lowest among the chemical components within each phase. A SiO₂–Al₂O₃ scatter plot of pottery samples from each phase at the Longhucun site was generated using Origin software (Fig. 6).

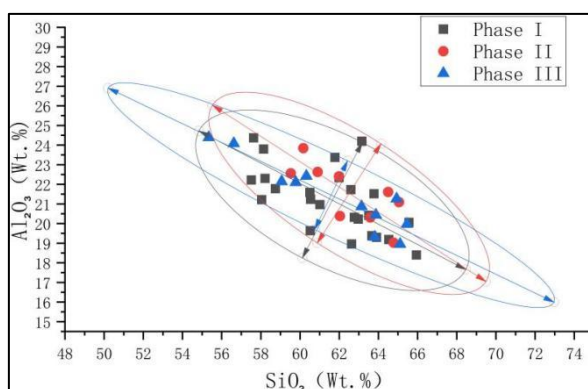


Fig. 6. SiO₂–Al₂O₃ scatter plot of pottery from each phase at the Longhucun site.

As shown in the figure, the Phase I samples show relatively wide compositional dispersion, with SiO₂ contents ranging from 57% to 66% and Al₂O₃ contents from 18% to 24%. The confidence ellipse is relatively broad, suggesting variation in clay procurement strategies or ceramic recipes during this phase. The Phase II samples are more concentrated, with SiO₂ at

approximately 59%–65% and Al_2O_3 at approximately 19%–24%, and the overall distribution is shifted slightly toward higher alumina, suggesting that clay procurement strategies became more stable. The Phase III samples show a marked increase in dispersion, with SiO_2 contents ranging 55.34% to 65.46% and Al_2O_3 from 18.95% to 24.39%. The main cluster shifted toward higher silica and lower alumina, while a few individual samples shifted toward lower silica and higher alumina; the confidence ellipse is elongated along the diagonal.

Overall, all data points generally fall within the same broad area, and no outliers are completely separated from the main group or form a separate cluster. The mean values of SiO_2 and Al_2O_3 , the major components, vary only within a limited range across the three phases, indicating that no fundamental replacement of raw material sources occurred in pottery production at the Longhucun site from the late Shang to the middle Spring and Autumn period. However, from Phase I to Phase III, the major components of the pottery from the Longhucun site underwent an evolutionary trajectory of “relative dispersion → concentration → renewed dispersion and a shift toward the lower right.” In particular, the data from Phase III show increased dispersion and a shift toward higher silica and lower alumina, indicating that certain adjustments were made in sand tempering ratios or clay procurement practices during the later phase.

3.3.2.2. Diachronic analysis of typical trace elements

Because clay minerals differ in their trace element contents depending on regional and geological conditions, and because pottery essentially does not exchange elements with the surrounding environment during firing, trace element analysis can be used to investigate provenance and raw material sources [19]. To investigate diachronic changes in the raw materials of pottery from the Longhucun site, this study selected five trace element ratios— $\text{Cr}_2\text{O}_3/\text{NiO}$, NiO/CoO , $\text{Rb}_2\text{O}/\text{SrO}$, $\text{ZrO}_2/\text{Rb}_2\text{O}$, and $\text{ZrO}_2/\text{TiO}_2$ —for phase-by-phase comparison. Among these, the $\text{Cr}_2\text{O}_3/\text{NiO}$ ratio mainly reflects the relative proportions of mafic and ultramafic heavy minerals versus ferromagnesian minerals [20] (Fig. 7a); the NiO/CoO ratio is related to Fe–Mn oxides and the degree of weathering [21] (Fig. 7b); the $\text{Rb}_2\text{O}/\text{SrO}$ ratio can indicate the relative contributions of clay minerals (feldspar, mica) versus carbonate or plagioclase components [22] (Fig. 7c); the $\text{ZrO}_2/\text{Rb}_2\text{O}$ ratio reflects the proportion of heavy minerals to fine-grained clay minerals [23] (Fig. 7d); and the $\text{ZrO}_2/\text{TiO}_2$ ratio is relatively sensitive to hydrodynamic sorting and the geomorphological context of clay procurement [24] (Fig. 7e). Trace element ratios such as Zr/Rb and Zr/Ti are widely used as provenance indicators [25].

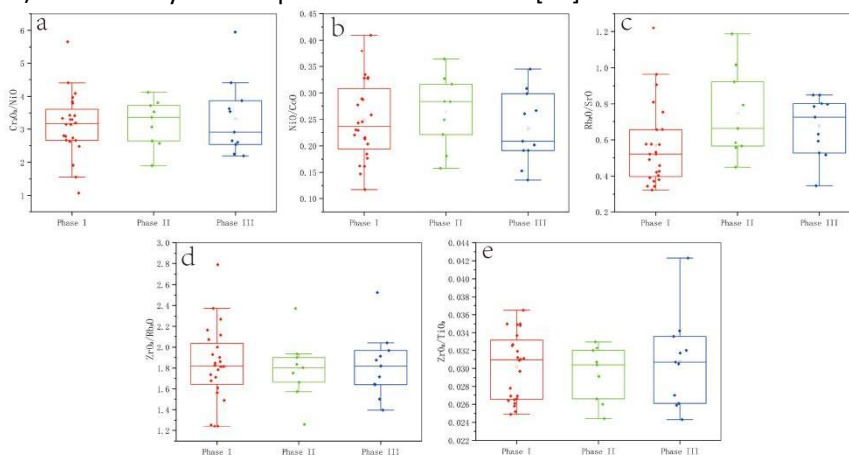


Fig. 7. Box plots of trace element ratios in pottery from the Longhucun site

Results show that in Phase I, the $\text{Cr}_2\text{O}_3/\text{NiO}$ ratio is widely distributed, with a maximum value of 5.66 and a minimum value of 1.07; the NiO/CoO ratio is relatively low and dispersed; and the $\text{ZrO}_2/\text{TiO}_2$ ratio has a median of about 0.031 and an interquartile range (IQR) of about 0.006, indicating considerable differences in raw material sources or recipes and relatively diverse clay procurement landforms. In Phase II, most ratios become more concentrated; the $\text{Cr}_2\text{O}_3/\text{NiO}$ ratio has a slightly higher median and the smallest dispersion; the NiO/CoO ratio rises to about 0.28 and is most stable; and the $\text{ZrO}_2/\text{TiO}_2$ ratio has a median of about 0.030 and an IQR of about 0.006, reflecting relatively stable raw material selection, possibly using a single clay type or a few

clay types. In Phase III, the $\text{Cr}_2\text{O}_3/\text{NiO}$, NiO/CoO , and $\text{ZrO}_2/\text{TiO}_2$ ratios again become more dispersed; the IQR of the $\text{ZrO}_2/\text{TiO}_2$ ratio increases to about 0.008, with a maximum value of 0.042 (sample 036), indicating increased diversity in clay procurement landforms. In contrast, the median $\text{Rb}_2\text{O}/\text{SrO}$ ratio increases continuously from about 0.52 in Phase I to about 0.66 in Phase II and about 0.73 in Phase III, suggesting systematic changes in clay mineral composition or a gradual decline in the practice of adding calcium-phosphate materials. The median $\text{ZrO}_2/\text{Rb}_2\text{O}$ ratio remains relatively stable, ranging from 1.71 to 1.82 across the three phases, indicating that the basic mineral framework of the raw materials did not undergo fundamental replacement from the late Shang to the middle Spring-and-Autumn period. Together, these characteristics indicate that pottery raw materials at the Longhucun site underwent an evolution from “relative diversity” to “relative stability” and then to “renewed differentiation.”

3.3.2.3. Diachronic analysis of anomalous components

Elements with a coefficient of variation (CV) > 20% are regarded as highly variable (potentially anomalous) elements in the chemical compositions of pottery samples from the Longhucun site, and samples with Z-scores > 2 or < -2 are considered anomalous for that element. Based on the XRF data from the 44 samples, anomalous elements and associated samples were identified. Combined with the three-phase chronological division of the Longhucun site, the results are presented in Table 8.

Table 8. Summary of anomalous elements at the Longhucun site.

Phase	n	P_2O_5 Mean (wt.%)	Range	CV(%)	Anomalous samples ($\text{P}_2\text{O}_5 > 2.5\%$)
Phase I	24	1.91	0.10~3.86	57.95	8 (33.33%), 001、012、015、016、017、021、026、029
Phase II	9	1.23	0.17~2.76	76.00	2 (22.22%), 037、044
Phase III	11	0.81	0.15~1.78	76.10	0
Phase	n	MnO Mean(wt.%)	Range	CV(%)	Anomalous samples (MnO>0.3%)
Phase I	24	0.15	0.02~0.89	156.00	4 (16.67%), 003、009、024、033
Phase II	9	0.04	0.02~0.09	53.63	0
Phase III	11	0.13	0.04~0.40	81.85	1 (9.09%), 036
Phase	n	Fe_2O_3 Mean(wt.%)	Range	CV(%)	Anomalous samples ($\text{Fe}_2\text{O}_3 > 9.5\%$)
Phase I	24	7.68	5.05~12.13	22.06	4 (16.67%), 009、013、016、035
Phase II	9	7.55	5.84~9.62	16.97	1 (11.11%), 034
Phase III	11	8.32	6.43~11.07	16.35	2 (18.18%), 008、030
Phase	n	NiO Mean($\mu\text{g/g}$)	Range	CV(%)	Anomalous samples ($\text{NiO} > 120\mu\text{g/g}$)
Phase I	24	71	33~199	48.89	2 (8.33%), 009、033
Phase II	9	64	49~99	26.63	0
Phase III	11	72	37~126	43.69	1 (9.09%), 030
Phase	n	Na_2O Mean(wt.%)	Range	CV(%)	Anomalous samples ($\text{Na}_2\text{O} < 0.2\%$)
Phase I	24	0.90	0.11~1.43	36.03	1 (4.17%), 019
Phase II	9	0.82	0.05~1.39	51.88	1 (11.11%), 034
Phase III	11	0.97	0.38~1.43	39.14	0
Phase	n	MgO Mean(wt.%)	Range	CV(%)	Anomalous samples ($\text{MgO} < 0.5\%$)
Phase I	24	0.87	0.41~1.73	43.50	2 (8.33%), 001、029
Phase II	9	0.87	0.57~1.15	22.24	0
Phase III	11	1.10	0.46~1.57	32.89	1 (9.09%), 023
Phase	n	SrO Mean($\mu\text{g/g}$)	Range	CV(%)	Anomalous samples ($\text{SrO} > 400\mu\text{g/g}$)
Phase I	24	339	145~471	23.32	4 (16.67%), 001、012、020、026
Phase II	9	255	169~331	25.47	0
Phase III	11	271	207~346	16.15	0
Phase	n	SO_3 Mean($\mu\text{g/g}$)	Range	CV(%)	Anomalous samples ($\text{SO}_3 > 500\mu\text{g/g}$)
Phase I	24	114	0~400	106.51	0
Phase II	9	377	0~964	97.62	3 (33.33%), 034、042、043
Phase III	11	615	86~2197	93.01	6 (54.55%), 005、008、022、023、030、036

Note: The sample size of Phase II is relatively small, and the analytical results are for reference only. CV = relative standard deviation.

Phase-by-phase statistics reveal clear temporal variations in anomalous elements of pottery from the Longhucun site. The mean P_2O_5 content declined continuously; high-P samples occur only in Phases I and II and disappear entirely in Phase III. The mean contents of MnO, NiO, and MgO first decreased and then increased; high-Mn, high-Ni, and low-Mg samples all appear in Phase I, disappear in Phase II, and reappear in Phase III. The mean SrO content was highest in Phase I (339 $\mu\text{g/g}$), decreased markedly in Phase II (255 $\mu\text{g/g}$), and rose slightly in Phase III (271 $\mu\text{g/g}$) but remained lower than in Phase I. High-Sr samples ($>400 \mu\text{g/g}$) occur only in Phase I. The mean SO_3 content increased continuously, and the number of high-S samples increased from 0 in Phase I to 3 in Phase II and 6 in Phase III, indicating a marked increase in S anomalies. The mean Fe_2O_3 content was relatively stable, although the proportion of high-Fe samples increased slightly in Phase III. Overall, this pattern suggests that Phase I (late Shang to early Western Zhou) shows the greatest diversity of anomalous elements, including P, Sr, Mn, Fe, Ni, Na, and Mg. Phase II (early to middle Western Zhou) shows markedly weakened anomalies, with only P, Fe, Na, and S anomalies present. Phase III (middle and late Western Zhou to middle Spring and Autumn period) exhibits a partial resurgence of anomalies, with Mn, Fe, Ni, and Mg anomalies reappearing, whereas P and Sr anomalies do not recover, and S anomalies intensify markedly.

3.4. Analysis of significantly anomalous components

P_2O_5 , MnO, and SO_3 are the three most significantly anomalous components at the Longhucun site. R-mode cluster analysis shows that P_2O_5 clusters closely with CaO and SrO, MnO groups with Fe–Mn oxides such as Fe_2O_3 , NiO, and CoO, while SO_3 is separated individually together with ZrO_2 at a relatively large distance from the main cluster in the raw-data dendrogram, although it shifted into the mafic/heavy mineral group after CLR transformation. This cluster structure suggests that the three types of anomalies may have different causal mechanisms.

Physical and chemical changes may occur during the burial of pottery, and elements such as P, Ca, Mg, Ba, and S may be affected by the burial environment [26,27]. Recent studies have also documented post-depositional alteration of alkali elements in archaeological ceramics [28]. We have found that high-P phenomena also occur in compositional analyses of pottery from some pre-Qin period sites in the Sichuan Basin, such as Sanxingdui [29] and Maqing in Hanyuan [30]. The high-P characteristics of pottery unearthed from these two sites appear to be related to chronological factors.

If the high-P characteristics of pottery from the Longhucun site were caused purely by burial contamination, P should be more enriched on vessel surfaces or within fissures, and the degree of contamination should be positively correlated with burial duration. Elemental mapping of high-P samples from Longhucun shows that P is not enriched in localized areas, as in samples 021 and 026 (Fig. 8a, b). We also noted that high-Sr samples overlap with high-P samples. The chemical properties of Sr are similar to those of Ca, and during burial Sr can substitute for Ca in carbonate minerals; however, it should also be randomly distributed rather than concentrated only in Phase I at Longhucun. Sr may also be adsorbed by clay minerals, in which case it should correlate with Al_2O_3 ; however, the correlation coefficient between SrO and Al_2O_3 in the Longhucun pottery samples is only -0.05 , which makes this possibility less likely. Nevertheless, a contribution from burial contamination cannot be entirely excluded.

Bone powder contains Ca, P, and Sr simultaneously (with Sr substituting for Ca in the hydroxyapatite lattice), whereas plant ash contains, in addition to mainly potassium carbonate (K_2CO_3), mineral elements such as P, Ca, and Mg; P in ash occurs mostly as water-soluble or acid-soluble phosphates. Given that Sr anomalies co-vary with P at the Longhucun site, we tentatively suggest that the two may share a common source, possibly from the addition of calcium phosphate materials (bone powder or plant ash), and that this practice may have been abandoned after the middle and late Western Zhou. However, some high-P samples from Longhucun do not contain high Sr, and some high-Ca samples are not high-P. In addition, the relatively small number of samples analyzed means that the high-P anomalies may not all result from differences in production technology; burial contamination may also be a contributing factor. Therefore, the calcium phosphate addition hypothesis should be regarded as one plausible explanation among several.

The most pronounced Mn anomaly occurs in sample 009, where MnO reaches 0.89%, the highest value in the assemblage, and is accompanied by high Fe_2O_3 content (12.13%). Mn is stable during high-temperature firing, neither volatilizing nor migrating; during burial, Mn can

migrate under reducing conditions, but it should also be randomly distributed. Other samples from the same stratigraphic layer as sample 009 (a pottery bottle) do not exhibit high-Mn characteristics, which may rule out contamination from the same layer. XRF elemental mapping clearly shows that Mn in sample 009 is concentrated on the cross-section of the pottery (Fig. 8c). We therefore suggest that the extreme MnO anomaly in sample 009 may be related to the incorporation of Mn-rich clay material during production. However, post-depositional Mn migration under reducing conditions cannot be completely ruled out. High-Mn samples number four in Phase I (003, 009, 024, and 033), disappear in Phase II, and comprise only one sample in Phase III (036), which may indicate that the use of Mn-bearing clay raw materials was episodic, although the small sample size limits the strength of this inference.

SO₃ is separated individually together with ZrO₂ in the R-mode cluster analysis, at a relatively large distance from the main cluster, and shows no covariant relationship with P, Mn, or Fe, indicating that its anomaly is independent of raw material and technological signals. Sample 022 has the highest SO₃ content in the entire assemblage, reaching 2197 µg/g, with a Z-score of +4.84. XRF elemental mapping shows that S in this sample exhibits an irregular, diffuse distribution (Fig. 8d). Sample 022 was recovered from kiln Y10. Samples 005 and 008 from kiln Y1 have SO₃ contents of 595 µg/g and 522 µg/g, respectively, both above the mean, indicating that SO₃ is generally elevated in kiln-related units. Other high-S samples, including 005, 008, and 023, also come from kilns or from strata and ash pits not far from kilns. In contrast, the proportion of high-S samples from units unrelated to kiln activity is extremely low. This spatial distribution strongly suggests that the SO₃ anomaly at the Longhucun site is closely associated with kiln activity, although a contribution from burial contamination cannot be entirely excluded. Relatively concentrated charcoal particles were observed in several ash pits, kilns, and cultural layers at the site. The presence of charcoal in the kilns directly attests to the use of fire in pottery production, whereas charcoal in the surrounding ash pits and cultural layers may reflect a broader range of fire-related activities, including kiln operation and waste disposal. This is consistent with the broader environmental archaeological record of the Chengdu Plain, where related studies have shown a notable increase in anthropogenic fire activity closely linked to pottery production and other craft activities since the late Neolithic [31]. Given this context, three possible explanations can be proposed for the SO₃ anomaly. First, during long-term use of the kiln, fuel combustion and the oxidation of sulfides in the clay would have enriched sulfur in the kiln wall and surrounding deposits; after the kiln was abandoned and reused as an ash pit or refuse pit, sulfur-bearing substances may have further penetrated into pottery buried there. Second, during firing in the kiln, a sulfur-rich atmosphere may have caused sulfur to become fixed in the surface layer or cross-section of the ceramic body. Third, the burial environment near the kiln (such as ash pits and ash ditches) may itself have had a high sulfur content as a result of fire-related activities, leading to secondary contamination after the pottery was buried. Whichever explanation applies, the spatial clustering of the SO₃ anomaly suggests that its formation is more likely related to kiln activity than to random contamination in an ordinary burial environment.

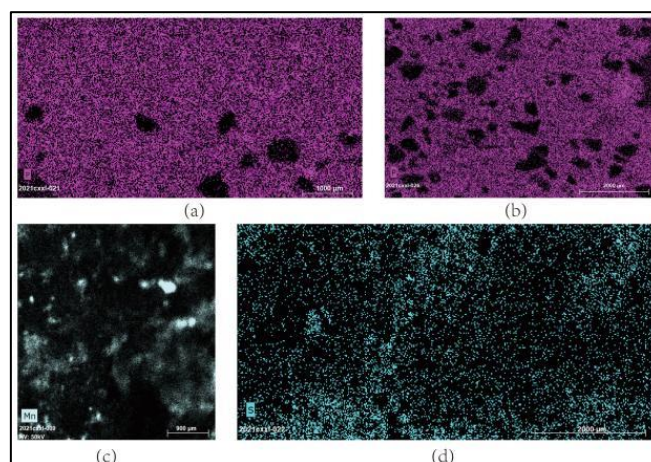


Fig. 8. XRF mapping of anomalous samples from the Longhucun site.

(a) Sample 021, P; (b) Sample 026, P; (c) Sample 009, Mn; (d) Sample 022, S.

It should be emphasized that the anomalous elements discussed above may have multiple origins, including raw material variability, production technology, and post-depositional processes. Distinguishing among these factors requires further micro-contextual, experimental, and petrographic evidence. The interpretations presented here are therefore tentative and should be tested with additional samples and controlled experiments.

4. Discussion

Few compositional studies of pottery have been carried out across the Chengdu Plain as a whole, with the most representative cases being the Sanxingdui [29] and the Jinsha site [32]. Recent multi-technique analysis of Jinsha pottery has provided additional compositional data [33]. The Sanxingdui study mainly published data for nine oxides in pottery, whereas the Jinsha study reported data for only eight oxides. Although additional trace element data were not published, the available data from both cases indicate that SiO_2 and Al_2O_3 remain the principal components of pottery from the Sanxingdui and Jinsha sites. To further examine the similarities and differences in pottery production technology between the Longhucun site and these two sites, we plotted the mass percentages of SiO_2 and Al_2O_3 in pottery from the three sites (Fig. 9).

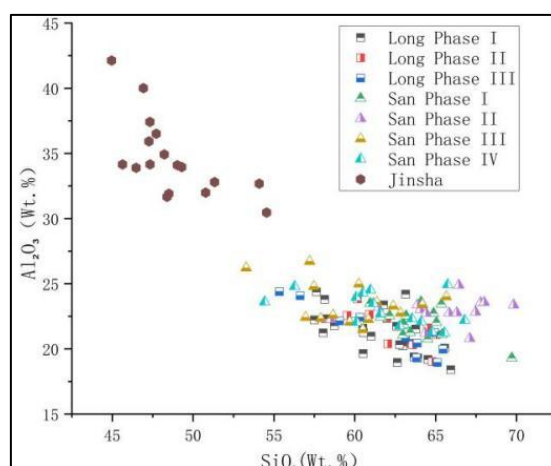


Fig. 9. SiO_2 – Al_2O_3 scatter plot of pottery unearched from the Longhucun, Sanxingdui, and Jinsha sites.¹

Based on currently available published data, the SiO_2 – Al_2O_3 scatter plot of the major components of pottery from the Longhucun, Sanxingdui, and Jinsha sites reveals distinct systems of raw material selection among the analyzed samples from the three sites. The Jinsha site (Min River basin) is characterized by high alumina ($\text{Al}_2\text{O}_3 \approx 30$ – 42%) and low silica ($\text{SiO}_2 \approx 45$ – 53%), forming a completely separate cluster in the plot. By contrast, Longhucun and Sanxingdui (Tuo River basin) are characterized by high silica ($\text{SiO}_2 \approx 55$ – 70%) and moderate alumina ($\text{Al}_2\text{O}_3 \approx 18$ – 26%). The two overlap substantially, indicating a high degree of consistency in clay raw material selection and suggesting that they may have shared a clay resource system within the same drainage basin.

In terms of diachronic change, the samples from Longhucun Phases I and II are relatively concentrated, with the main cluster falling between approximately 58% – 65% SiO_2 and 20% – 24% Al_2O_3 . The samples from Longhucun Phase III show a marked increase in dispersion, with some samples shifting toward higher silica and lower alumina (e.g., approximately 63% – 65.5% SiO_2 and 19% – 20% Al_2O_3), while a few individual samples retain high-alumina characteristics (e.g., samples 008 and 030, with approximately 24% Al_2O_3 and 56% SiO_2). It should be noted, however, that the mean values of Longhucun Phase III differ only to a limited extent from those of Phases I and II (Al_2O_3 : $21.19\% \rightarrow 21.54\% \rightarrow 21.45\%$; SiO_2 : $61.65\% \rightarrow 62.50\% \rightarrow 61.59\%$), and the main body still belongs to the high-silica, moderate-alumina system, with no systematic replacement of raw material sources having occurred. The increased dispersion in Phase III may reflect certain

¹ In this figure, the major component values for the Jinsha site pottery samples are all midpoints, varying by no more than 0.1% .

adjustments in sand-tempering proportions or clay procurement practices during the later phase, but no new, distinct raw material type had yet formed. This trend is broadly consistent with the evolutionary direction of the various phases at Sanxingdui: Sanxingdui Phases III and IV likewise exhibit differentiation toward higher alumina or higher silica, yet overall still fall within the high-silica, moderate-alumina field. Similar diachronic trends have been observed in other Bronze Age ceramic assemblages in China [34]. Longhucun Phase III partially overlaps with Sanxingdui Phase IV in the plot, indicating that the two sites maintained similar raw material selection traditions from the middle and late Western Zhou to the middle Spring and Autumn period; however, the greater dispersion of Longhucun Phase III suggests that its late-phase clay procurement or recipe adjustments were more pronounced.

In addition, our research indicates that pottery production technology at the Sanxingdui, Longhucun, and Jinsha sites during the Shang–Zhou period was highly consistent. In terms of firing technology, the kiln structures at all three sites are dominated by figure-of-eight-shaped horizontal kilns. Some kilns may have had perforated floors or grate structures, and there were also a certain number of firing pits (pit kilns). In terms of forming techniques, coil building predominates, accompanied by hand modeling and a small amount of slab building, and most pottery vessels bear traces of wheel finishing. Some vessels, such as high-necked jars, ring-foot jars, and flared-mouth urns, were made by separately constructing the neck and body, or the foot ring and body; the techniques used to attach and reinforce these separately formed parts include fine clay reinforcement, pressure reinforcement, and riveting reinforcement [35]. These observations are consistent with the long-term continuity in pottery production traditions documented for the Chengdu Plain [5].

In summary, the Min River and Tuo River basins may have each developed independent clay raw material supply systems, but the two regions shared similar technological genes in pottery production, together forming a basic pattern of "differentiation in raw materials and shared technological origin" in pottery production in the Chengdu Plain during the Shang–Zhou period. Such integrated chemical and contextual approaches are essential for reconstructing ancient ceramic production systems [7].

The main conclusions of this study are as follows: First, the 44 Shang – Zhou pottery samples from the Longhucun site exhibit an overall chemical profile characterized by high silica (mean $\text{SiO}_2 = 61.81\%$), moderate alumina (mean $\text{Al}_2\text{O}_3 = 21.33\%$), and high iron (mean $\text{Fe}_2\text{O}_3 = 7.81\%$). The major elements show little variation, and the CVs of most trace elements are below 20%, indicating a concentrated raw material source. This pattern is consistent with local production using a restricted, probably local clay source, although geological reference samples would be required to confirm on-site procurement.

Second, diachronic analysis indicates that the major components of all three phases belong to a high-silica, moderate-alumina system, without evidence for a fundamental change in raw material characteristics sources having occurred. Nevertheless, the assemblage underwent an evolutionary trajectory of "relative dispersion → concentration → renewed dispersion," with a marked increase in dispersion in Phase III and some samples shifting toward higher silica and lower alumina. The median $\text{ZrO}_2/\text{Rb}_2\text{O}$ ratio remains relatively stable, ranging from 1.71 to 1.82 across the three phases, indicating that the basic mineral framework of the raw materials remained unchanged over the long term. whereas the continuous increase in the median $\text{Rb}_2\text{O}/\text{SrO}$ ratio suggests changes in clay mineral composition or a decline in calcium phosphate addition.

Third, the significantly anomalous components are P_2O_5 , MnO , and SO_3 . P_2O_5 clusters with CaO and SrO , and some high-P samples co-vary with high Sr, which may indicate the addition of calcium phosphate materials from the late Shang to the early Western Zhou, possibly abandoned in later phases. MnO groups with Fe_2O_3 and NiO , and sample 009 has an MnO content as high as 0.89%, suggesting the incorporation of Mn-bearing clay raw materials, which appears to have been episodic. SO_3 is independent of the main cluster, and sample 022 has a content as high as 2197 $\mu\text{g/g}$. Most high-S samples come from kilns such as Y1 and Y10 or from nearby units, suggesting that the sulfur anomaly is likely related to pottery-making activities or kiln use, although a burial contribution cannot be ruled out.

Fourth, comparison with Sanxingdui and Jinsha reveals the existence of distinct systems in Shang–Zhou pottery production in the Chengdu Plain: Jinsha (Min River basin) is characterized by high alumina and low silica and forms an independent cluster; Longhucun and Sanxingdui (Tuo River basin) are characterized by high silica and moderate alumina and overlap substantially; and

the pottery-making technologies at the three sites are also highly consistent. This indicates that the Longhucun, Sanxingdui, and Jinsha sites together constitute a basic pattern of “differentiation in raw materials and shared technological origin.”

Finally, the Longhucun site is a specialized pottery-production workshop with 19 kilns, forming the largest kiln cluster in the Chengdu Plain apart from the Jinsha site. The presence of a pottery seal interpreted as a potter’s or workshop’s marker further supports its specialized nature. This study provides the first systematic compositional dataset for pottery from this key workshop site, offering a basis for understanding raw material selection, paste recipes, and production organization during the Shang–Zhou period in the Chengdu Plain.

This study has several limitations. First, the number of Phase II samples is relatively small ($n = 9$), so some statistical results have limited representativeness and the relevant conclusions should be treated with caution. Second, the comparative data for Jinsha and Sanxingdui are drawn from previously published research, and information on the chronology, vessel forms, and archaeological contexts of the analyzed samples is limited, which constrains the precision of the comparison. In particular, the XRF analysis of Jinsha pottery by Xu et al [33] . was based on only three samples; given the very small sample size, these data are unlikely to be representative of the Jinsha assemblage as a whole and were therefore not included in the comparative analysis. Nevertheless, even if these three samples were considered, they would not alter the overall pattern of raw material differentiation observed in this study. Third, this study did not systematically collect samples of clay, sterile subsoil, or kiln wall deposits from the vicinity of the site, so no geological end-members could be established, and the discussion of "mixed clay procurement" or "raw material recipes" can only remain at the level of qualitative inference. Fourth, because the compositional data are subject to the closure effect, the correlation coefficients and cluster groupings reported here should be regarded as exploratory rather than definitive statistical inferences. These limitations await further refinement and improvement through the addition of more samples and systematic geological background surveys and petrographic analyses in future research.

Supplementary Material

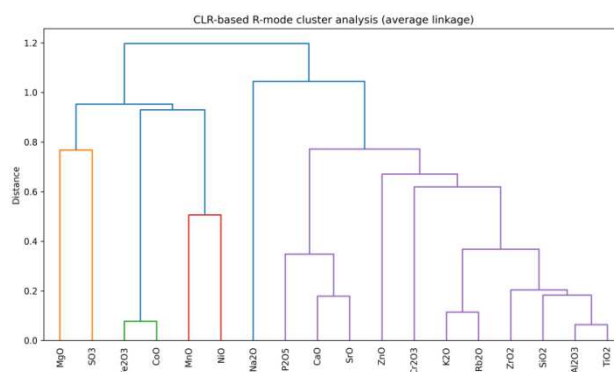


Figure S1. CLR-based R-mode cluster analysis of pottery from the Longhucun site (average linkage, correlation distance). Zero values were replaced by $0.65 \times$ the minimum non-zero value before CLR transformation.

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