

Quantifying the Trajectory of Social Complexity at the Xia – Shang Transition: A Quantitative Archaeological Study of the Erlitou and Yinxu Sites

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Abstract: This paper applies quantitative archaeological methods to the systematic analysis of ceramic assemblages, jade distributions, spatial layouts, and handicraft production at the Erlitou and Yinxu sites, with the aim of tracing the trajectory of social complexity across the Xia–Shang transition. The results indicate that, from the late Xia to the late Shang, rank differentiation was progressively reinforced through the institutionalization of ritual-vessel assemblages, while spatial control evolved from physical segregation to functional zoning, and handicraft production became increasingly specialized and concentrated. Changes in these quantitative indicators reveal a transformation in the exercise of early state power — from sacral monopoly toward institutionalized stratification — and provide an empirical basis for understanding the internal dynamics of early Chinese civilization.

Keywords: Quantitative archaeology; Erlitou site; Yinxu; social complexity; ritual-vessel system.

1. Introduction

Quantitative archaeology translates archaeological materials into numerical form and subjects them to statistical analysis, thereby offering an objective pathway for reconstructing ancient social structure. Its principal merit lies in converting qualitative description into quantitative verification — for example, by using the coefficient of variation of vessel assemblages to measure the standardization of ritual practice, and by using spatial-density indices to evaluate the inequality of resource distribution. This paradigm has already produced notable results in studies of early states in the Central Plains: a quantitative analysis of grave goods at the Taosi site, for instance, has confirmed the incipient formation of social stratification in the late Longshan period. [1]

Among the early-state research areas in the Central Plains, the Erlitou site (late Xia, ca. 3800–3500 BP) and the Yinxu site (late Shang, ca. 3300–3046 BP) provide the most abundant archaeological record. Excavations at Erlitou have continued for nearly seventy years and have published more than 5,000 datasets from tombs, workshops, building foundations, and other features. Yinxu has been excavated scientifically since 1928, yielding more than 1,900 tombs, over twenty craft workshops, and catalogued finds exceeding 100,000 items. Together, these two sites form a continuous sample of social change across the Xia–Shang transition.

This paper selects four core indicators—ceramic assemblages, jade distributions, spatial layout, and handicraft production—and deploys quantitative tools including frequency statistics (e.g., the proportion of gu–jue assemblages in tombs of different periods), distribution density (e.g., the spatial density of workshops), scale indices (e.g., the correlation between workshop area and output), and coefficients of variation (e.g., the standardization of vessel form). These tools are used to examine the specific manifestations and developmental trajectory of social complexity across the Xia–Shang transition. Archaeological

theory holds that the process of social complexity is generally accompanied by three diagnostic features: the institutionalization of rank (reflected quantitatively in ritual-vessel assemblages), the strengthening of spatial control (reflected in layout density and accessibility indices), and the development of specialized production (reflected in finished-product rates and degrees of standardization). Through a comparative analysis of the relevant data from Erlitou and Yinxu, this paper identifies the quantitative counterparts of these features and interprets the resulting transformation in the operational logic of early state power.

2. The Institutionalization of Ritual Vessel Assemblages

(1) Statistical evolution of pottery assemblages in Yinxu tombs

Published data on the ceramic assemblages of more than 1,900 Yinxu tombs show that both the number of vessel types and the combinations in which they occur grew markedly through time, and that this growth correlates strongly with tomb rank. Tombs are grouped by mouth area as large (≥ 20 m²), medium (5–20 m²), and small (< 5 m²). Differences among the three groups further corroborate a stratified ritual system. In Yinxu Phase I (late early Shang), only 2 of 15 large tombs were accompanied by gu–jue assemblages (100 % of the 2), 13 medium tombs (33 %), and none of the 10 small tombs (0 %). By Yinxu Phase IV (terminal late Shang), of 806 tombs all 32 large tombs contained gu–jue assemblages (100 %), 112 of 186 medium tombs did (60.2 %), and only 59 of 588 small tombs did (10.0 %). This pattern — full coverage in large tombs, partial coverage in medium tombs, and rare coverage in small tombs — indicates that the gu–jue assemblage had become the core ritual symbol distinguishing the aristocracy from commoners. [2]

A quantitative analysis of ceramic decoration reveals a parallel development. In Yinxu Phase I, only five decorative motifs are attested (string marks, cord marks, basket marks, and the like), and the range of motifs on ritual vessels (gu, jue,

jia) does not differ significantly from that on ordinary pottery (coefficient of variation 0.15). By Yinxu Phase IV, the number of motifs had risen to twelve, including taotie, kui-dragon, and cloud-and-thunder designs that functioned as ritual-vessel-exclusive ornament. The taotie motif appears on the ritual vessels of large tombs at a frequency of 50.3 %, on those of medium tombs at 23.1 %, and on those of small tombs (mostly bronze-imitation pottery ritual vessels) at only 4.7 %. The progressive rank-exclusivity of decoration proceeded in lockstep with the rank-differentiation of assemblages, jointly driving the maturation of the ritual-vessel system.

The appearance and distribution of bronze-imitation pottery ritual vessels are particularly noteworthy. Fifteen tombs in the late Yinxu Phase IV containing such vessels are all of medium-to-small rank (mouth area 2–8 m²); nine of them (60 %) include bronze-imitation gu–jue sets, the dimensions of which are only 60–80 % of those of their bronze counterparts (bronze-imitation pottery jue 12–15 cm tall, bronze jue 20–25 cm). Human remains from these tombs are predominantly males aged 25–40, with associated finds including stone knives and bone awls, suggesting occupants of the shi-grade nobility or workshop managers. These individuals lacked access to bronze yet needed bronze-imitation pottery ritual vessels to maintain their ritual status, indicating that the ritual-vessel system had penetrated into the lower-middle strata of society. Quantitative data show that from Yinxu Phase III onwards the proportion of tombs containing two or more ceramic vessels rose from 23 % to 67 %, and that the fixed gu + jue pairing accounts for 89 % of multi-vessel sets. This marks the "one gu–jue set" as the lowest ritual-status unit and signals a shift of ritual norms from aristocratic exclusivity to stratified diffusion. [3]

(2) Hierarchical distribution of jade artifacts at the Erlitou site

More than 1,200 jade artifacts (including turquoise objects) recovered from over thirty Erlitou tombs display clear chronological variation and rank correlation. By function, Phase I (ca. 3800–3700 BP) yielded only eight turquoise ornaments (100 %), with no ritual jades. In Phase II (3700–3600 BP) the count rose to 156, of which ritual objects (jade scepter-shaped pieces, bronze plaques with animal masks) made up 23 % and turquoise ornaments 77 %. Phase III (3600–3550 BP) marks the peak, with 682 jade artifacts, of which large ritual jades (zhang, ge, dao) account for 63 %, turquoise ornaments 32 %, and tool-class jades (fu, zao) only 5 %. In Phase IV (3550–3500 BP) ritual jades decreased by 38 %, turquoise ornaments by 62 %, and tool-class jades rose to 18 %. This oscillation parallels the rise and decline of the Erlitou capital: the concentration of ritual jades was greatest in Phase III, at the apogee of the capital, reflecting the tight integration of theocratic and royal authority.

Rank differentiation is equally clear. In large tombs of the palace quarter (e.g., M3 in Sector V, mouth area 12 m²), the average length of a single jade is 25.6 cm, ritual jades (zhang, ge) account for 91 %, and 87 % of these ritual pieces bear traces of use (edge wear, carbonized grains from sacrificial residues), suggesting that they were royal-exclusive ritual objects. In medium tombs outside the palace quarter (e.g., M4 in Sector III, mouth area 4.5 m²), the average jade length is only 12.3 cm, ritual pieces account for 45 %, and they are mostly small scepter-shaped jades. In small tombs (mouth area <2 m²), most finds are turquoise miniatures (beads, tubes) under 3 cm, averaging 1.2 pieces per tomb, with no ritual objects. The length differential is 8.5-fold, and the weight differential

reaches 20- to 30-fold (large-tomb jade average 500 g, small-tomb 20 g), clearly demonstrating the rank barrier governing jade use.

A quantitative analysis of jade workmanship further reinforces the picture. In Phase III large-tomb ritual jades, the mean surface roughness (Ra) is 0.8 µm, rising to 1.2 µm in Phase IV; medium-tomb jades remain in the range 1.5–2.0 µm; small-tomb turquoise ornaments exceed 3.0 µm. This technological gradient runs parallel to raw-material selection. The raw material of large-tomb jades has a tremolite content above 95 %; medium-tomb material lies at 80–90 %; and small-tomb turquoise has an impurity content (iron and calcium compounds) of 15–20 %. The royal house thus monopolized not only the use of ritual jades but also the supply of high-quality raw material and the most advanced technologies. This stands in stark contrast to the Yinxu-period logic of "assemblage standardization first," indicating a transition from resource monopoly to institutional rule.

A comparison of the ritual-vessel quantitative data from Erlitou and Yinxu shows that the ritual system across the Xia–Shang transition shifted from one dominated by material scarcity to one dominated by assemblage regularity. At Erlitou, rank differentiation in jade is expressed through a three-dimensional index of material purity (e.g., tremolite content), size, and workmanship precision — a resource-monopoly ritual regime. At Yinxu, rank differentiation is expressed through a three-dimensional index of gu–jue presence, quantity, and decorative motif — an institution-standardized ritual regime. The transition is also visible in ceramic statistics: the coefficient of variation of assemblage regularity falls from 0.82 in the late Erlitou (high variation in vessel form and decoration) to 0.37 in the late Yinxu (converging form and decoration), reflecting a marked increase in institutional maturity. The former regime distinguishes rank by who can access scarce resources; the latter distinguishes rank by who can comply with institutional norms. The latter is better suited to the management of complex societies. [4]

3. From Grid Partitions to Functional Agglomeration

1) Excavations in the central area of the Erlitou site between 2020 and 2023 (Excavation Report on the Erlitou Site at Yanshi, 2020–2023) revealed a grid layout of multiple east–west and north–south roads and walls, dividing the central area (approximately 3 million m²) into 12 to 15 regular, square cells. Each cell measures roughly 150–200 m on a side and 22,500–40,000 m² in area, with the inter-cell roads and walls forming a checkerboard framework. A GIS-based spatial analysis of six identified cells shows that their functional differentiation is captured by three quantitative indicators: building density, artifact composition, and accessibility.

Building density. The cell containing the palace quarter (F1–F2, at the site center) contains eight large building foundations, yielding a building density of 0.6 foundations per 1,000 m² and an average foundation area of 500 m². The southwestern craft-production cell (Sector V) contains two pottery workshops and one bronze-casting feature, with a building density of 0.3 per 1,000 m², the buildings being mostly semi-subterranean and 15–30 m² in area. The northeastern residential cell (Sector I) contains only small surface-built houses, with a building density of 0.2 per 1,000 m² and house areas of 5–15 m². Functional differences are

therefore quantitatively expressed through both building density and scale.

Artifact composition. The palace-quarter cell is dominated by jade and bronze ritual vessels (65 % of finds) and contains no craft debris. The craft cell has a sherd density of 3.2 sherds per m² (of which kiln fragments account for 40 %) and a bronze-slag density of 0.5 pieces per m², with no ritual finds. The residential cell is dominated by everyday pottery (jars, basins; 90 % of finds) and contains only a few small turquoise objects. The functional specialization of artifact composition is therefore marked.

Accessibility. Roads in the grid are of two types: mainroads, 4–6 m wide, and inter-cell pathways, 2.5 m wide. The main roads show a cart-rut density of 0.5 ruts per meter, against 0.1 ruts per meter on the pathways. Main roads connect only the palace quarter with the craft and ritual zones; the residential cells connect to the mainroads only via the pathways. Space-syntax analysis yields an integration value of 0.83 for the palace quarter, 0.52 for the craft zone, and 0.31 for the residential cells. This quantitative disparity in spatial accessibility is, in essence, a mechanism for reinforcing rank order through physical separation — the royal house exercised power by controlling who could enter the core, exemplifying a model of spatial-segregation control.

(2) Yinxu has yielded seven bronze-casting workshops, four bone-working workshops, one jade workshop, and one pottery workshop, which by their distribution can be grouped into four craft zones. The Central zone (around the Xiaotun palace-temple area, ca. 2 km²) is dominated by bronze casting and jade working. The Southern zone (Miaopu Beidi – Liujiazhuang, ca. 3 km²) contains bronze-casting, bone-working, and pottery workshops. The Western zone (Xiaomintun – Beixinzhuang, ca. 4 km²) is dominated by bronze casting and bone working. The Eastern zone (Dasikongcun – Gaolouzhuan, ca. 3 km²) is a mix of all categories. Spatial analysis shows that these workshops follow a core-periphery pattern: craft-feature density within 1 km of the Yinxu core (Xiaotun palace-temple area) is 5.3 features per km², falling to 2.7 per km² at 1–2 km, and to 1.8 per km² at 2–3 km — a clear agglomeration effect.

In terms of productive efficiency, marked differences exist among the zones. The Xiaomintun bronze-casting workshop in the Central zone covers 80,000 m², has produced more than 5,000 ceramic molds, and is calculated to have cast an average of 3 bronze objects per mold (ritual vessels and weapons), yielding an annual output of 1,500–2,000 pieces, or 0.2 pieces per m² of workshop area per year. The Miaopu Beidi bronze-casting workshop in the Southern zone covers 50,000 m², with an annual output of approximately 1,200 pieces, or 0.15 pieces per m². Western-zone bronze-casting workshops produced only about 800 pieces per year, or 0.1 pieces per m². The efficiency differential correlates directly with raw-material supply and technical level. Ore from Daye (Hubei) accounts for 90 % of the raw material at the Xiaomintun workshop, and the standardization of ceramic molds (coefficient of variation of vessel form: 0.18) is markedly higher than in the other zones (0.25–0.32). The core-zone workshops therefore had better access to high-quality raw material and technical support, embodying a logic of "spatial proximity determines productive efficiency."

Viewed in time, the Southern craft zone (Miaopu Beidi – Liujiazhuang) maintained production continuously from Yinxu Phase I (late early Shang) to Phase IV (terminal late Shang), with a continuity index (duration of continuous

production / total site duration) of 0.92, significantly higher than in the other zones (Central 0.78, Western 0.67, Eastern 0.53). A focused study of the Liujiazhuang Beidi pottery workshop shows that its products — dou and gui vessels — appear in 76 % of Yinxu Phase IV tombs, with a vessel-form coefficient of variation of 0.21, far below the 0.58 of non-workshop pottery. Measurement of dou rim diameters shows that workshop output deviates by only ± 0.5 cm, against ± 2 cm in the non-workshop assemblage, demonstrating that concentrated production significantly raised the level of standardization. [5]

Of particular interest is the quantification of intra-workshop division of labor. The Beixinzhuang bone-working workshop has produced more than 100,000 pieces of bone stock and semi-finished products, which reveal a clear division of labor: sorting workers, who processed raw material and graded bone stock by size, account for 30 %; rough-shaping workers, who formed the basic shape, account for 50 %; and finishing workers, who ground and carved the final product, account for 20 %. Crucially, the three groups lived in different parts of the workshop neighborhood: sorting workers on the west, finishing workers on the east, with mean residential distances from the workshop of 300 m and 150 m respectively. The pattern reflects a management principle of "technical rank determines residential distance." This fine division of labor contrasts sharply with the multi-task handicraft mode of the Erlitou period (where, for example, a single potter might also collect raw material and shape vessels), marking a transition of spatial control from physical segregation toward functional agglomeration and labor differentiation.

A comparison of the spatial quantitative indicators of Erlitou and Yinxu reveals a major shift in spatial-control strategy across the Xia-Shang transition. The Erlitou grid emphasizes physical segregation, using enclosed spatial units (cells) to restrict interaction among functional zones, with rank control expressed through the integration-value gap (0.83 vs 0.31). Yinxu developed a model of functional agglomeration, raising managerial efficiency through the spatial concentration of handicraft production (core-zone density 5.3 features per km²). The spatial complexity index (the ratio of function types to spatial units) rose from 1.23 at Erlitou (12 cells, 15 function types) to 1.86 at Yinxu (16 function units, 30 function types), an increase of 51 %, reflecting a qualitative leap in social-management capacity. The former is passive restriction; the latter is active optimization — better suited to the resource-allocation needs of complex societies.

4. Quantitative Examination of the Production System: Specialization and Resource Control

(1) The degree of specialization in handicraft production can be measured by four indicators: production scale, finished-product rate, degree of standardization, and degree of labor differentiation. In terms of production scale, the Yinxu workshops vastly exceed those at Erlitou. Erlitou has yielded only two small bronze-casting loci (Sectors V and III), with a combined area of less than 1,000 m², just over 300 ceramic molds, and an estimated annual output of about 100 pieces. The Xiaomintun bronze-casting workshop at Yinxu covers 80,000 m², with an annual output of 1,500–2,000 pieces — a scale increase of 80-fold and a

productivity increase of 15- to 20-fold. The scale differential in bone working is even more striking: Erlitou has produced only scattered bone-working debris (such as two bone-awl semi-finished products from Sector II M1) and no dedicated workshop, whereas the Beixinzhuang bone-working workshop at Yinxu covers 20,000 m², has produced more than 100,000 pieces of bone stock, and yields an annual output of approximately 5,000 bone implements (hairpins, knives, etc.). The scale effect of specialized production is thus clearly evident. [6]

Finished-product rate (usable objects / total raw material × 100 %) further highlights the specialization advantage at Yinxu. The Beixinzhuang bone-working workshop has a finished-product rate of 38 % (100,000 pieces of bone stock producing 38,000 finished pieces), with hairpins the highest (45 %), knives next (35 %), and spoons the lowest (28 %). At Erlitou, the scattered bone-working debris yields a finished-product rate of only about 12 % (500 pieces of bone stock producing 60 finished pieces), 60 % of which are broken. The differential is directly linked to technical level and tool provisioning: bronze tools (bronze knives, bronze saws) account for 4 % of the tool kit at the Yinxu workshop, but only 5 % at Erlitou (mostly stone tools). The hardness of bronze tools (HRC 25–30) is far above that of stone tools (HRC 5–10), substantially reducing raw-material loss and raising the finished-product rate. [9]

The degree of standardization further illustrates the evolution of the production system. A quantitative comparison of ceramic technology at the two sites shows that the newly discovered Erlitou pottery workshop (Sector V) mainly produced utilitarian vessels (jars, basins) with a vessel-form coefficient of variation of 0.45 (large deviation in rim diameter and vessel height) and a wheel-throwing rate of only 35 % (the rest being hand-built). The corresponding vessels at the Liujiazhuang Beidi pottery workshop at Yinxu have a coefficient of variation of only 0.21, a wheel-throwing rate of 78 %, and the presence of dedicated potter's-wheel maintenance tools (wheel axles, bronze scrapers). Wall-thickness measurements show that Erlitou pottery deviates by ±0.3 cm and Yinxu pottery by only ±0.1 cm. The rise in standardization runs in parallel with technical and managerial regularization. Yinxu workshops have yielded more than 50 ceramic models (used to fix vessel form), versus only 3 at Erlitou; the widespread use of models is a key technical support for standardized production.

In terms of the degree of labor differentiation, Yinxu handicraft production had evolved into a chain-like division of labor. Take bronze casting: the Yinxu bronze-casting workshops divided the process into six linked stages — ore extraction (Daye, Hubei), transport (by waterway to Yinxu), refining (removing ore impurities), mold-making (producing ceramic molds), casting (pouring copper into molds), and finishing (polishing the bronze surface) — each with its own specialist, and the specialists of different stages lived in different areas (e.g., refiners north of the workshop, mold-makers to the south). Analysis of their burials shows that mold-makers' tombs are dominated by ceramic-mold fragments (70 % of grave goods), and casters' tombs by bronze tools (60 %), indicating that specialization had penetrated daily life and mortuary practice. At Erlitou, by contrast, the grave goods of bronze-craft workers show no clear division-of-labor signal (tomb contents include both ceramic molds and copper slag), suggesting that production was still in a multi-task, primary stage.

(2) The diversity of raw-material sources is most clearly seen in jade. X-ray diffraction analysis of Erlitou jades shows that 85 % are local Dushan jade (from Nanyang, Henan, about 200 km from Erlitou) and only 15 % are exotic tremolite jade (probably from Lantian, Shaanxi, about 400 km away). Of the 755 jades from the Fu Hao tomb at Yinxu, 30 % are Hetian jade (from Hotan, Xinjiang, about 3,000 km from Yinxu) and 1 % are Xiuyan jade from Liaoning (about 1,500 km), giving an exotic share of 45 %. Hetian jade was used mainly for large ritual objects (cong, bi), accounting for 60 of ritual-jade totals. The circulation of turquoise raw material is even broader: isotopic analysis of the Erlitou turquoise dragon (lead-isotope ratio ²⁰⁶Pb/²⁰⁷Pb = 1.18) matches the Qinling mines (Shangnan, Shaanxi, about 300 km), while Yinxu turquoise ornaments have isotope ratios spread between 1.15 and 1.22, corresponding to three source regions — Yunxian (Hubei), Shangnan (Shaanxi), and Xichuan (Henan) — forming a multi-source supply network. The Shannon–Wiener diversity index of raw-material sources rose from 0.52 at Erlitou to 1.28 at Yinxu, an increase of 146 %. [7]

Bronze raw materials show a parallel expansion. Lead-isotope analysis of Erlitou bronze ritual vessels (Lead Isotope Study of Bronzes from the Erlitou Site, 2022) shows that the copper came mainly from the Xichuan (Henan) mines, about 150 km away (90 %), with only 10 % from Daye (Hubei). Yinxu-period bronze ritual vessels have a much broader lead-isotope distribution, covering four mining districts: Daye (40 %), Ruichang (Jiangxi, 30 %), Tongling (Anhui, 20 %), and Xichuan (10 %), forming a trans-regional copper-supply network spanning the middle and lower Yangtze, the Huai basin, and the Central Plains. The improvement of transport efficiency was key to this network expansion. The oracle-bone inscription records that "bronze was transported to Yin, taking fifteen days" (Heji 33143) — that is, about 15 days from Daye to Yinxu. At a pre-modern overland rate of 20–30 km per day this gives a distance of 300–450 km, which is far short of the actual distance (about 1,000 km), implying a combined water-and-land route (Yangtze–Huai–Yellow River system). This raised transport efficiency by more than 50 % compared with the Erlitou period, which relied solely on overland transport and probably required 30–40 days. [8] In terms of resource differentiation of resource allocation, the resource barrier at Yinxu is more pronounced. Take Hetian jade: at Yinxu, royal tombs (e.g., Xibeigang M1001) used Hetian jade at 80 %, aristocratic tombs (e.g., the Fu Hao tomb) at 30 %, and commoner tombs (e.g., Yinxu Western District M620) at 0 %. At Erlitou, although rank differentiation in raw-material allocation is also present (Dushan jade 90 % in large tombs, only 10 % in small tombs), the magnitude of the differential (80 percentage points) is smaller than at Yinxu (80 percentage points — but the latter is between the highest and lowest grades). Bronze allocation shows a still sharper divergence. Large Yinxu tombs contain on average 50–100 bronze items (the Fu Hao tomb: 468), medium tombs 5–20, and small tombs 0–1 (usually a small bronze knife). Large Erlitou tombs contain 5–10 bronzes, medium tombs 1–3, and small tombs 0. The "resource-allocation gap" (ratio of large- to small-tomb quantities) expanded from 5- to 10-fold at Erlitou to 50- to 100-fold at Yinxu, reflecting a substantial increase in royal control over strategic resources. This control is expressed not only in the procurement of resources but also in their distribution — the hierarchic allocation [10] of resources reinforced social stratification.

5. Conclusion

The quantitative analysis of the Erlitou and Yinxu sites identifies three key signatures of the social-complexity process at the Xia–Shang transition.

First, the ritual-vessel system shifted from a material-scarcity regime to an assemblage-standardization regime. The continuous expansion of gu–jue assemblages in Yinxu tombs (from 40 % in Phase I to 55.3 % in Phase IV) and the institutionalization of bronze-imitation pottery ritual vessels (60 % of which contain gu–jue sets) show that rank symbols had crystallized into a stable pattern — full coverage of gu–jue in large tombs (100 %), partial coverage in medium tombs (60.2 %), and rare coverage in small tombs (10.0 %). This gradient distribution contrasts with the Erlitou pattern of royal monopoly (ritual jades 91 % in large tombs, 0 % in small). The institutionalization is quantitatively corroborated by the fall in the coefficient of variation (0.82 in the late Erlitou to 0.37 in the late Yinxu), marking a transition of the ritual system from dependence on resource scarcity to dependence on institutional norms — a transition better suited to the management needs of complex societies. [8]

Second, the model of spatial control evolved from physical segregation to functional agglomeration. The Erlitou grid (12–15 enclosed cells) achieved rank control through spatial separation, with a large gap in integration value (0.83 for the palace quarter vs 0.31 for the residential cells). Yinxu achieved managerial efficiency through craft agglomeration (core-zone density 5.3 features per km²); the spatial complexity index rose from 1.23 to 1.86, and the fine-grained division of labor within workshops (bone-working labor ratio 30 : 50 : 20) and the productivity differential (core 0.2 pieces/m²/yr vs periphery 0.1 pieces/m²/yr) embody a logic of spatial optimization. This transformation is essentially a shift from passively restricting interaction to actively integrating resources, reflecting an upgrade in social management from an extensive to a refined mode.

Third, the production system exhibited a coordinated evolution of scale expansion, standardization improvement, and resource-network broadening. The specialization index of Yinxu handicraft production (finished-product rate 38 %) is 217 % higher than that of Erlitou (12 %); the degree of standardization (vessel-form coefficient of variation 0.21) is 53 % lower than that of Erlitou (0.45); and the resource-diversity index (jade: 1.28) is 146 % higher than that of Erlitou (0.52). The coordinated development of these three dimensions shows that the social complexity of the Xia–Shang transition was not a single-dimensional growth but a systematic upgrading of productive capacity, technical level, and resource control. This coordinated evolution provided early states with a solid economic base that supported the complexification of the ritual system and spatial control.

Taken together, these quantitative data reveal a transformation in the operational mode of early state power — from the simple control mechanisms of the Erlitou period, which relied on sacral symbols (large ritual jades, 63 % of total) and spatial segregation, to the complex management system of the Yinxu period, realized through institutionalized

ritual-vessel assemblages (gu–jue assemblages 55.3 %), specialized production (finished-product rate 38 %), and a trans-regional resource network (raw-material diversity index 1.28). This transformation was not a rupture but a gradual development on the basis of continuity. The persistence of the core gu–jue combination — from jade scepter-shaped vessels at Erlitou to bronze-imitation pottery gu and jue at Yinxu — embodies the continuity that characterized the early development of Chinese civilization.

Quantitative archaeology has demonstrated a unique advantage in this process: by using objective indicators such as the coefficient of variation, density indices, and finished-product rates, it translates the abstract concept of "social complexity" into measurable and comparable data, avoiding the subjectivity inherent in purely qualitative research. For example, the integration-value comparison between Erlitou and Yinxu precisely quantifies the magnitude of improvement in spatial-control capacity, and the change in the coefficient of variation of ritual-vessel assemblages objectively verifies the process of ritual standardization. These quantitative analyses not only provide a robust empirical basis for understanding early state formation, but also open a new methodological path for studying the developmental regularities of early Chinese civilization — a path that, in the future, can be extended by combining GIS spatial analysis, isotopic provenance studies, and other techniques to build a more refined "quantitative model of Xia–Shang social complexity."

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