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# A GIS approach to the spatial organization and social structure of the Jiaojia cemetery, eastern China

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Ziqi Li<sup>1,2</sup>, Qingwei Meng<sup>1,2</sup>, Xiaoning Lu<sup>3</sup>, Ziyu Fang<sup>1,2</sup>, Fen Wang<sup>1,2</sup>, Zhongming Tang<sup>1,2</sup>✉ & Hao Wu<sup>1,2</sup>✉

The Jiaojia site is located in the piedmont plains on the north side of the Taiyi Mountains (泰沂山脉). It was a regional centre in the northern part of Shandong during the middle to late stages of the Dawenkou culture (3500 BCE–2600 BCE), and it is currently the earliest prehistoric walled site discovered in the lower reaches of the Yellow River. We performed spatial analysis using ArcGIS combined with mortuary data and statistical analysis. We examined the spatial distribution of the 86 burials excavated at the site's northern district in 2016 and discussed its implications for understanding the social structure of the Jiaojia site back to the Neolithic times.

The middle to late Dawenkou period (3500 BCE–2600 BCE) was crucial for the origin of civilisation in the lower Yellow River region of China<sup>1</sup>. In-depth research on the Dawenkou culture has provided important clues for exploring the processes of social complexity<sup>2</sup>. By ~3500 BCE, during the middle stage of the Dawenkou culture, it is widely accepted that a stratified society had begun to take shape in this area<sup>3</sup>. Externally, the Dawenkou culture started to expand its influence into the Central Plains, while internally, social differentiation accelerated and intensified, giving rise to a number of sites with regional centrality, some of which developed into walled settlements. By the late stage, after 3000 BCE, this developmental trajectory continued. Alongside the formation of a stratified society, an emerging social elite began to take shape. Settlement patterns during this period typically exhibited a three-tiered hierarchy of large, medium, and small sites, and the number of walled settlements increased. Mortuary evidence also reflects pronounced social differentiation and disparities in wealth—sets of objects with the characteristics of ceremonial assemblages became prominent in burials and gradually institutionalised. Around the same time, regions such as the Central Plains, western Liaoning, and the middle and lower reaches of the Yangtze River also independently embarked on their respective paths toward civilisation. While maintaining their distinct cultural traditions, the newly emerging elites in these regions actively participated in interregional exchange and interaction.

The Jiaojia site represents a rapidly emerging regional central settlement in northern Shandong during this critical transitional stage of early civilisation development. It is currently the earliest known prehistoric walled settlement in the lower reaches of the Yellow River and holds a significant position in the study of the civilisation process in the Haidai region. The site is located on the pre-mountainous plains north of the Taiyi Mountain Range in Zhangqiu District, Jinan City. Approximately 12 km to the north

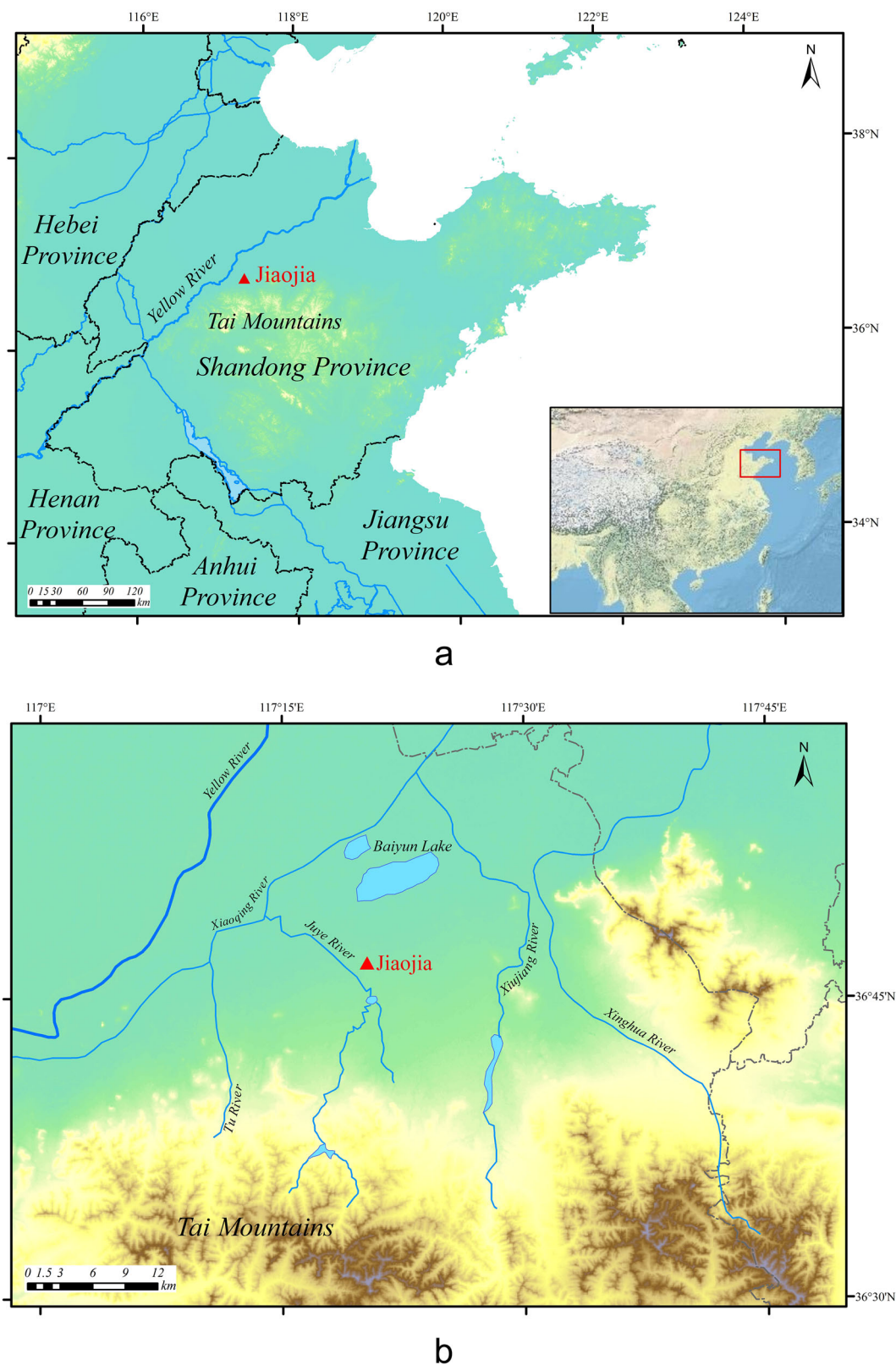
lies the Xiaoqing River, while the Juye River flows southeast to northwest just 500 metres west of the site. To the south, it is situated about 5 km from Chengziya (城子崖), the eponymous site of the Longshan culture (Fig. 1). Archaeological surveys around the site, combined with observations of stratigraphic sections, suggest that the total site area exceeds 1 million square metres, with Dawenkou cultural remains covering ~800,000 square metres.

As crucial remnants of ancient society, tombs not only carry rich historical information but also deeply reflect the social organisation, cultural practices, and family relationships of their time. They provide authentic and abundant materials for examining the diverse systems, ideologies, and technological developments of antiquity. Currently, over 500 Dawenkou culture tombs have been discovered at the Jiaojia site, exhibiting clear signs of social differentiation. Among the high-grade tombs, archaeologists identified the earliest known example in China of a 'triple-layered burial container and double-layered burial container' structure with a detailed report. Wooden burial containers—burial containers and outer burial containers—were used in over 70% of cases. In addition to complete and finely crafted ceramic assemblages in white, painted, and black pottery, large tombs also yielded power-symbolising objects such as jade axes, bone carving tubes, and sets of jade ornaments. Therefore, analysing the distribution and spatial structure of tombs at the Jiaojia site is not only a critical window into understanding the social formation of the Dawenkou culture but also an important channel for exploring prehistoric social transformation and the trajectory of early civilisation<sup>4</sup>.

We selected a cemetery sector with relatively complete exposure within the excavated area of the Jiaojia site. On the one hand, we employed GIS technology to analyse the temporal, spatial, and social attributes embedded in a total of 86 tombs from this sector, with the aim of gaining deeper insights into the social stratification and organisational structures they reflect. On the

<sup>1</sup>Key Laboratory of Archaeological Sciences and Technology (Shandong University), Ministry of Education, Jinan, China. <sup>2</sup>School of Archaeology, Shandong University, Jinan, 250100, China. <sup>3</sup>Museum of the War of Peoples Resistance Against Japanese Aggression, Beijing, 100071, China.

✉ e-mail: [tangzm@sdu.edu.cn](mailto:tangzm@sdu.edu.cn); [whmm1204@163.com](mailto:whmm1204@163.com)



**Fig. 1 | Geographical context of the Jiaoja site. a** Geographical location of the Jiaoja site within China and Shandong Province; **b** Topographic features of the surrounding area of the site (base maps cropped and modified according to the Shandong standard map service, ‘Natural Geography of Shandong Province, 2 sheets, 1:1000000’).

other hand, this study also focuses on evaluating the feasibility and effectiveness of applying GIS techniques to cemetery analysis. By tracking the spatiotemporal changes of tomb distribution and integrating the results into a broader social framework, we aim to provide new ideas and references for related research. This approach also offers novel methods for conducting

comparative studies on social structure across different cultural contexts and contributes to the internationalisation and interdisciplinary integration of archaeological research.

While existing GIS applications in mortuary archaeology have primarily examined macro-scale patterns across regions or entire cemetery

**Table 1 | Comparison table of burial stages at the Jiaojia site**

Phasing of the Dawenkou Culture	Burial staging at the Jiaojia site	
Phase 5	Phase 1	Early stage
Phase 6	Phase 2	
Phase 7	Phase 3	
Phase 8	Phase 4	Middle stage
Phase 9	Phase 5	
Phase 10	Phase 6	Late stage

complexes, the socio-spatial dynamics within partial sectors remain underexplored. Here, we present a case study in the use of GIS that combines chronological sequencing and spatial zoning frameworks to analyse temporal-spatial dynamics at a partial sector of the cemetery. This methodology advances cemetery spatial analysis by integrating typo-chronological analysis of funerary assemblages, enabling refined investigations into both burial space organisation and stratified social structures.

## Methods

GIS has become an essential and widely recognised tool in archaeological research<sup>5–7</sup>. The application of geographic information systems (GIS) in archaeology has provided strong support for exploring the spatial distribution of tombs and the structures of social relations<sup>8,9</sup>. Through the collection, management, analysis, and visualisation of spatial data, GIS can reveal the distribution and changes of different types of remains in a specific time period and uncover hidden information about social relations in sites, providing a fresh perspective and methodology for the study of archaeology. Through systematic synthesis and review, GIS applications have undergone notable advancements<sup>10–13</sup>. Contemporary researchers leverage GIS to transform vast archaeological datasets into spatially referenced layers<sup>14,15</sup>, employing techniques such as viewshed analysis<sup>16,17</sup>, optimal path calculation<sup>18</sup>, predictive modelling<sup>19</sup> and 3D reconstruction<sup>20,21</sup>. These spatial analyses are synergistically integrated with multidisciplinary datasets, including zooarchaeological/archaeobotanical records<sup>22</sup>, artefact distributions and cultural landscape features. Such integrative frameworks facilitate holistic investigations into themes like environmental archaeology<sup>23</sup>, settlement archaeology<sup>24,25</sup>, landscape archaeology<sup>26,27</sup> and large-scale demographic trends. Concurrently, 3D digital archiving technologies enhance cultural heritage preservation<sup>28,29</sup>, enabling dynamic visualisations of ephemeral or vulnerable archaeological contexts.

In mortuary archaeology, GIS has emerged as a pivotal methodology, enabling systematic approaches to synthesise and interpret spatial data. Contemporary methodologies focus on converting archaeological records—such as burial contexts, funerary objects, and osteological demographic data—into spatial data layers for quantitative analysis<sup>30</sup>. Among core techniques, viewshed analysis evaluates tomb visibility within ritual landscapes<sup>31</sup>, while predictive modelling identifies burial site suitability through environmental variables<sup>32,33</sup>. Complementing these, 3D reconstruction visualises tomb morphology and spatial hierarchies<sup>34,35</sup>, and optimal path analysis infers ancient mobility patterns to contextualise burial networks<sup>36</sup>. Kernel density estimation (KDE) further refines this framework by mapping temporal shifts in burial concentrations<sup>37</sup>. These address themes of ritual symbolism<sup>38</sup>, social hierarchy<sup>39</sup>, environmental adaptation, and cultural memory<sup>40</sup>.

Currently, GIS is used primarily to elucidate the spatial patterns of archaeological sites or is combined with bio-archaeology to focus on detailed human remains; however, an in-depth study of the spatial distribution of tombs over time using GIS is still lacking.

## Material introduction

The Jiaojia site was first identified during an archaeological survey in 1987, and by the end of 2024, a total of seven systematic excavation seasons had been conducted. Preliminary findings confirmed the existence of multiple

concentric large-scale defensive structures—city walls and moats—and uncovered the remains of a southern gate of the inner walled settlement. From the perspective of settlement changes, the excavated area underwent three major developmental stages during the Dawenkou cultural period: an early residential zone, a middle-stage cemetery, and a late residential zone.

In terms of relative chronology, the Jiaojia site belongs to the middle and late stages of the Dawenkou culture. According to information provided by the excavators, based on stratigraphic relationships and the typological changes of funerary objects, the tombs can be divided into six phases. These correspond to phases 5 through 10 of the Dawenkou cultural sequence proposed by Luan Fengshi<sup>41</sup>. The six phases can be further grouped into three stages: early, middle, and late (Table 1). Early-stage burials were mostly dug from beneath Layer 6 (the Dawenkou cultural layer) and were dominated by cooking vessels among the pottery. In Phase 3, tombs featuring a single burial container and outer burial container began to appear, possibly indicating the onset of social stratification. Middle-stage burials can be divided into two types: one continues to be dug from beneath Layer 6 and shares characteristics with early stage burials, likely representing a developmental continuation of the earlier burial group; the other type appears beneath Layer 5 (the Longshan cultural layer), where the proportion of cooking vessels decreases, fine ceramics become more prevalent, and white pottery emerges. Differences in tomb size and funerary objects increase, suggesting a heightened level of social differentiation. Late-stage burials are also found beneath Layer 5, but their overall number decreases. The pottery assemblage is dominated by small grey-black earthenware vessels, with painted pottery largely absent, suggesting a chronological gap between the late and middle stages.

Radiocarbon dating was conducted on human remains from 13 tombs at the site<sup>42</sup>. After calibration using dendrochronological data, the results can be divided into four chronological groups:

Group 1, represented by M98 and M124, corresponds to Phases 1–2. The mean calibrated date is 2882 BCE (95.4% confidence interval).

Group 2, represented by M158, M197 and M61, corresponds to Phase 3, with a mean calibrated date of 2785 BCE (95.4% confidence interval).

Group 3, represented by M55 and M182, corresponds to Phases 4–5. The mean calibrated date is 2746 BCE (95.4% confidence interval).

Group 4, represented by M17 and M21, corresponds to Phase 6. The mean calibrated date is 2582 BCE (95.4% confidence interval), showing a temporal gap from Group 3.

As the relative chronology and calibrated radiocarbon data reflect only the median values of each phase, the cemetery's actual span of use likely extended over ~400 years. While the early and middle stages are closely connected in time, a notable chronological hiatus in burials emerges during the late stage.

The tombs selected for this study are primarily located in the northern excavation area of the Jiaojia site, uncovered in 2016. To provide a more complete picture of the cemetery as a whole, 11 additional tombs from the northeastern edge of the 2017 excavation area were also included, bringing the total number of tombs considered to 112.

In addition, 15 empty tombs were identified within this area. Excavators have suggested that these may represent relocated burials. Owing to the lack of reliable information, and to avoid potential bias in the quantitative analysis, these tombs were excluded from the statistical dataset. Moreover, findings from the 2022 excavation season indicate that 11 tombs located at the southeastern edges of the 2016 northern area likely belong to different burial groups. These were also excluded from the statistical analysis.

As a result, this study focuses on a total of 86 tombs, including 56 from the early stage, 14 from the middle stage and 16 from the late stage. The 'study cemetery' refers exclusively to the dataset delineated above unless stated otherwise.

## Establishing the Jiaojia GIS database

The foundational step involved creating a comprehensive digital database derived from the 2016 excavation of 86 tombs in the northern district of the

Jiaojia site. The database systematically collated spatial data (e.g. tomb coordinates, orientation and intra-site location) and burial attributes (e.g. tomb area, depth and structural features such as burial container presence and tiered platforms). Additionally, it detailed records of funerary objects, including type (e.g. pottery, jade and bone artefacts), quantity, and placement. Biological information, such as the identifiable sex and age of the skeletons, was also taken into account. This database served as the backbone for subsequent spatial and statistical analyses, ensuring all variables were georeferenced and quantifiable.

### GIS-based temporal-spatial zoning and cluster analysis

Tombs were categorised into early, middle, and late stages in GIS using radiocarbon dates, typology and stratigraphy. Spatial analysis was employed to examine the spatial arrangement patterns of tombs from each stage, with particular attention to the potential existence of tomb groups.

Subsequently, descriptive statistics and GIS overlay analysis were integrated to analyse tomb ranking and spatial organisation. Tombs were classified into hierarchical grades using tomb size, burial furniture (burial containers, tiered platforms) and funerary objects' characteristics (quantity, typology), while mean artefact counts per phase were calculated to identify temporal patterns. GIS visualised spatial distributions, mapping tomb clusters, orientations and locations against grade classifications and artefact types to examine associations between burial attributes and cemetery layout. This integrative approach systematically linked statistical classifications with spatial relationships, forming the basis for interpreting social morphology through structured analysis of burial specifications and material culture distributions.

This structured pipeline—from data integration to spatial-statistical cross-validation—enabled a nuanced interpretation of how the cemetery layout reflected social organisation, providing a replicable framework for mortuary archaeology.

### Spatial modelling approaches

Three quantitative spatial modelling techniques were applied: Thiessen polygon partitioning, KDE and spatial constraint modelling. These models enable a more rigorous exploration of tomb distribution patterns and their social implications.

We used Thiessen polygons to divide the burial area spatially. Each polygon represents a tomb's influence zone, and adjacent polygons that share a boundary are considered neighbouring influence zones. Based on this, cluster analysis defines the boundaries of tomb groups within the study area. The Thiessen polygon is shown in Eq. (1).

$$V(s_i) = \{x \in M | d(x, s_i) \leq d(x, s_j), \forall j \neq i, s_j \in S\} \quad (1)$$

where  $d(x,s)$  denotes the distance function between two points  $x$  and  $s$ .

We employed KDE to perform spatial clustering analysis based on various attributes of the tombs. The goal was to identify distributional hotspots and levels of concentration, thereby integrating spatial location with burial characteristics. This approach helps reveal patterns of spatial distribution and their changes over time, reflecting underlying social transformations. The KDE formula is shown in Eq. (2).

$$\text{Density}(x, y) = \sum_{i=1}^n \left[ \text{Population}_i \frac{1}{h^2} \times K\left(\frac{d_i}{h}\right) \right] \quad (2)$$

where  $\text{Population}_i$  denotes the weight of the  $i$ th point,  $h$  is the search radius,  $d_i$  is the distance from the  $i$ th point to the centre of the raster cell at  $(x,y)$  and  $K$  is the kernel function.

Building on the quantitative analysis, this study further explores the social organisation of the Jiaojia cemetery through group analysis, incorporating both spatial location and funerary objects' attributes as dual constraints. The resulting groups exhibit strong internal similarity and clear inter-group differences, allowing for the quantification of spatial adjacency

and the modelling of social relationships among burial groups. The spatial constraint model used is K-nearest neighbour (KNN). As this group contains 70 samples, drawing on findings from previous studies, the recommended number of clusters typically falls below the square root of the sample size, which is  $\sim 8.3$  in this instance. At  $k = 8$ , the pseudo-F statistic attains its maximum, the coefficient of determination ( $R^2$ ) reaches its highest value, and the sum of squared deviations (SSD) is minimised, suggesting that this value of  $k$  is optimal for the present analysis.

The grouping variables include five key attributes: jade artefacts, pottery, tomb orientation, tomb size and number of burial containers. Owing to a temporal gap between the late-stage burials and those of the early and middle stages, the grouping analysis is limited to early- and middle-stage burials.

## Results

### Diachronic shift of cemetery spatial layout

Synchronicity is a necessary precondition for analysing the internal spatial organisation of the cemetery. Based on a comprehensive consideration of the stratigraphic relationships and the typological changes of funerary objects among the 86 tombs in the northern sector examined in this study—and with reference to the relative chronological framework established in the previous section—it can be determined that, except for the absence of tombs from Phase 1, burials from all other phases are represented within the study area. Specifically, the tombs can be grouped into three developmental stages: the early stage includes 56 tombs, with 31 and 25 tombs from Phase 2 and 3, respectively; the middle stage includes 14 tombs, with eight and six from Phase 4 and 5, respectively; and the late stage (Phase 6) includes 16 tombs (Fig. 2).

In the subsequent analysis, we employ the Thiessen polygon to construct polygons centred on individual tombs to explore spatial relationships, distribution density, and underlying patterns. To mitigate the limitations of the method's homogeneous distribution assumption, tomb size and tomb orientation were incorporated as weighted indices, thereby generating polygon networks for each stage (Fig. 3).

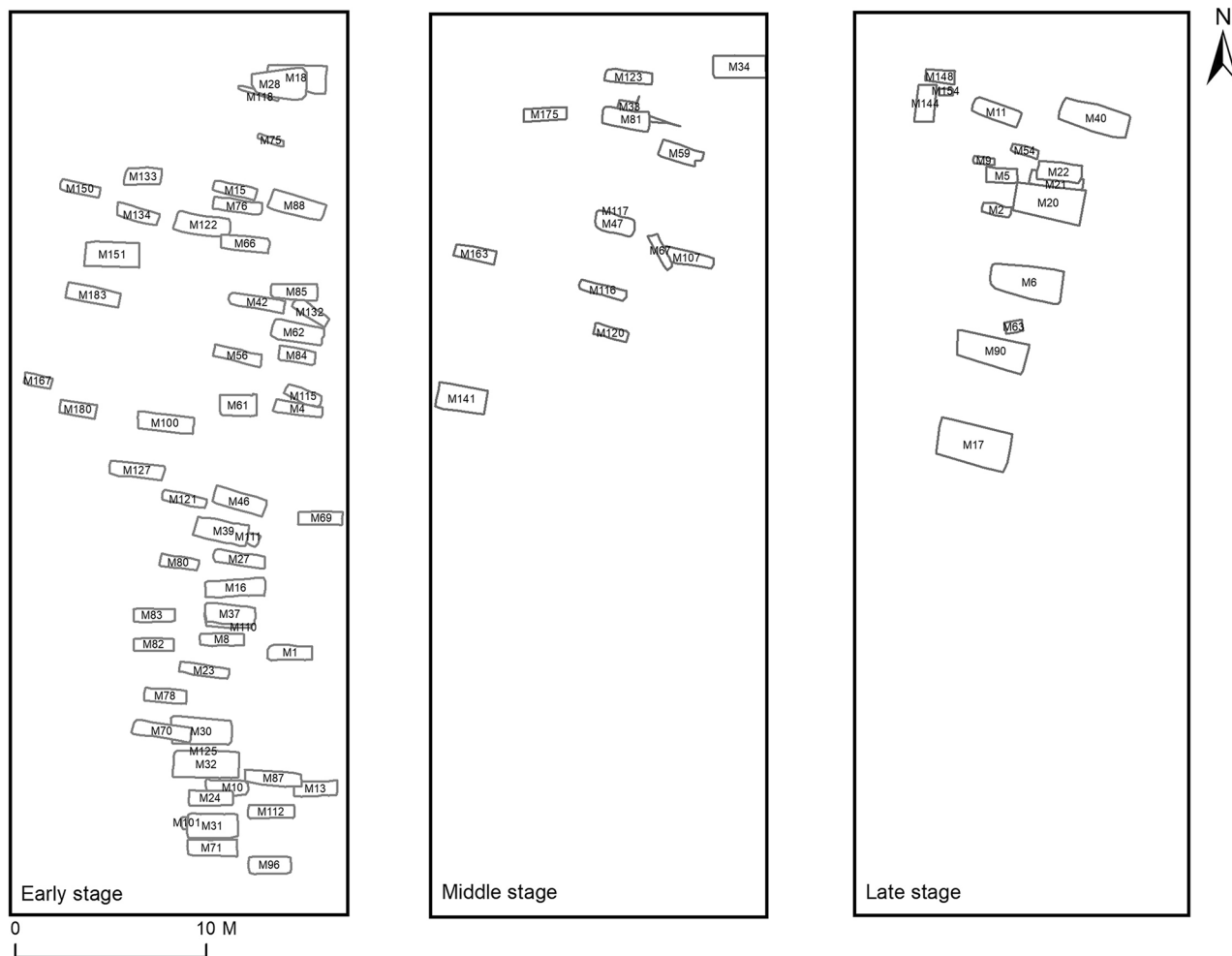
Focusing first on the early-stage spatial layout. This stage contains the largest number of tombs, accounting for 65.1% of the total sample. The tombs are distributed across a broad area and occupy nearly the entire northern cemetery zone, effectively delimiting the spatial extent available for middle- and late-stage tombs. The tomb chambers generally feature rectangular or rounded-rectangle plans. Most tombs are oriented either east–west or southeast–northwest, with azimuths ranging from  $84^\circ$  to  $124^\circ$ , indicating a certain degree of variability in tomb orientation that may imply the presence of multiple tomb groups or subgroups.

Based on the results of the Thiessen polygon analysis, the early-stage tombs can be subdivided into three groups: Group A in the southern sector, Group B in the northeastern sector, and Group C in the northwestern sector. Group A contains the largest number of tombs (30 in total) and can be further divided into subgroups Aa and Ab. The polygon shapes in subgroup Aa are relatively more dispersed than those in subgroup Ab. Tombs in Aa are generally arranged in two north–south rows. In contrast, the polygon geometry of Ab exhibits a certain symmetry: smaller, tightly clustered polygons are concentrated in the centre, while larger and more dispersed polygons are located on both sides. This pattern may reflect a more deliberately organised layout within this subgroup.

Group B consists of 19 tombs and can be subdivided into Ba, Bb, and Bc based on polygon aggregation and dispersal patterns. Subgroups Ba and Bb exhibit similar polygon morphologies and reflect a two-row north–south distribution. Subgroup Bc features larger, more dispersed polygons and is likely located at the northeastern periphery of the cemetery.

Group C has the fewest tombs, with only seven identified. It can be subdivided into Ca and Cb. The polygons in this group are generally large, indicating a sparse distribution of tombs and suggesting that this cluster may lie on the northwestern fringe of the cemetery.

Moving to the middle stage, all tombs from this stage are distributed in the northern half of the cemetery, corresponding to the spatial ranges of



**Fig. 2** | Shifting spatial layouts of the burials from the early to the late stage.

Groups B and C identified in the early stage. Except for M67, which has a relatively large tilt angle, tomb orientations generally align near east–west or slightly southeast–northwest, with orientation degrees ranging from 90° to 113°.

Notably, M47 is the burial of a middle-aged female, positioned with her head facing northwest and feet toward southeast, differing from the general cemetery pattern. Similarly, M175, a middle-aged male, is oriented with his head to the west and feet to the north. While these two tombs may represent non-local individuals, M47 contained locally typical funerary objects such as the folded-belly *ding* (鼎, a tripod cooking vessel with three legs) and tubular cups common in the Jiaojia cemetery. M175 yielded a white pottery *dou* (豆, a kind of high-footed dish) with a common form but distinctive ceramic fabric. Whether these individuals were indeed outsiders and a determination of their status within the settlement remains to be clarified through further analyses, such as DNA or strontium isotope studies.

Compared to the early stage, the number of tombs in this stage significantly decreases, and the Thiessen polygons generally cover larger areas, reflecting a more dispersed spatial arrangement. However, when these seemingly scattered middle-phase tombs are integrated into the corresponding early-phase groups, it is evident that many middle-phase tombs fill spatial gaps within these early groups without overlapping or disrupting existing tombs. This suggests that the middle-phase burials represent a natural continuation and expansion of the early groups. Specifically, M116 and M120 in the south can be assigned to early-stage Group Ba; M47, M67, M107, and M117 in the central area correspond to Group Bb; M34, M38, M59, M81, and M123 in the north belong to Group Bc; and M141, M163 and M175 in the southwest are affiliated with Groups Ca and Cb.

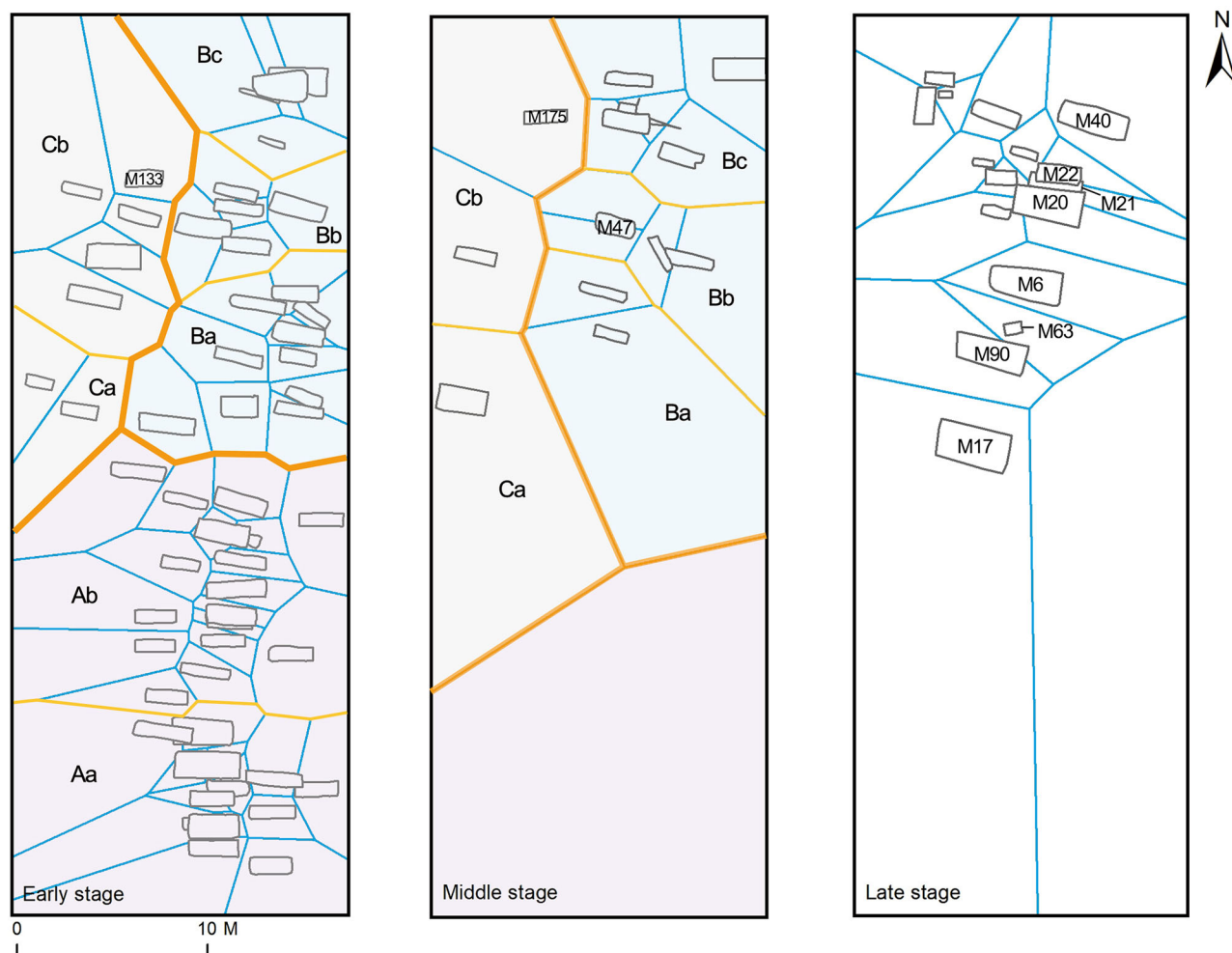
The late stage presents a distinct spatial pattern. Compared with the middle stage, the tombs from this stage are also concentrated in the northern part of the cemetery, but the geometry of their Thiessen polygons indicates a significantly more clustered spatial pattern. The characteristics of these tombs are more distinct and can be divided into two categories.

The first category consists of a row of large, high-status tombs located in the eastern sector. This row, aligned north–south, comprises five large tombs—M40, M20, M6, M90 and M17—characterised by standardised spacing and deliberate alignment. Each tomb features either a combination of burial container and outer burial container or high-status funerary objects, indicating carefully planned elite burials.

The second category includes nine tombs belonging to infants, children, and adolescents. Except for M63, located just north of M90, all are concentrated in the northwestern part of the cemetery. Tombs M21 and M22, situated north of M20, do not fit either group. Notably, M21 is a double female burial with both individuals interred supine and extended side-by-side but with their heads facing in opposite directions—a highly unusual burial custom.

Overall, the spatial organisation of the northern cemetery zone reveals a clear trajectory of change from early to late stages. In the early stage, 56 tombs were widely distributed across three main groups (A, B and C), further subdivided into seven subgroups.

Weighted Thiessen polygon analysis revealed internal hierarchical differentiation, with central zones of high density and peripheral areas of lower density. The predominantly east–west orientation, along with variation in azimuth, may suggest the coexistence of multiple social groups within a shared cemetery.



**Fig. 3** | Spatial layout of burials from the early to late stage in Thiessen polygons.

In the middle stage, 14 tombs contract toward the northern half of the cemetery. Their large polygon sizes reflect a looser spatial arrangement. However, their precise placement in previously unoccupied areas within early-stage groups indicates continuity with the earlier spatial framework.

In the late stage, 16 tombs restructured the cemetery layout. Five large tombs form a planned, evenly spaced north–south elite row in the eastern sector, while nine minors are clustered in the northwest. The spatial divergence between these two groups reflects an emerging degree of social stratification.

The spatial layout of the northern cemetery thus illustrates a broader transition from pluralistic coexistence to intensified social hierarchy. The carefully planned elite tomb row in the east and the emergence of a child-focused burial area in the northwest point to the institutionalisation of authority and a strengthening of social stratification. This pattern further demonstrates the analytical strength of the Thiessen polygon method in tracing transformations in spatial structure.

Nevertheless, the method’s static nature and its assumption of homogeneity present inherent limitations. A fuller understanding of the social meaning embedded in burial space requires integrating additional techniques such as spatial overlay and KDE. With this in mind, the following section will shift the focus to the tombs themselves, examining differences in tomb rank, special burial customs, and other indicators to reconstruct the social organisation across different stages.

**Burial ranking and social stratification**

The emergence and eventual establishment of a stratified society were likely driven by the development of productive forces, which led to the

accumulation and concentration of social wealth. As economic differentiation intensified, disparities in access to resources within the settlement gave rise to distinct social hierarchies, ultimately resulting in the formation of commoner and elite classes<sup>43</sup>.

There is a strong correlation between the social status of the dead and the characteristics of their burials—including the size and structure of tombs, the quantity and quality of funerary objects, and the presence of symbols of authority<sup>44</sup>.

Based on tomb construction, the number of burial containers, and the quantity and quality of funerary objects, the excavators have preliminarily classified the tombs into three categories: large, medium, and small. Building on this foundation, we applied a spatial grouping approach to further refine the hierarchical classification of tombs.

The basic procedure involves three steps. First, geographic coordinates are integrated with five key attribute datasets—jade artefacts, pottery, tomb orientation, tomb size and number of burial containers. After standardisation, a spatial proximity network is constructed using the KNN algorithm to quantify geographic relationships among tombs.

Next, spatially constrained clustering is applied, combining both spatial proximity and attribute similarity. Tombs that are geographically adjacent and exhibit high similarity in attributes such as jade artefacts are grouped together, ensuring strong intra-group homogeneity and significant inter-group differentiation. Statistical tests are employed to validate the significance of the clustering results.

Finally, each group is assigned a hierarchical grade based on key attributes. The spatial distribution of these hierarchical groups is then used

to infer the structure of social stratification and possible kinship-based organisation within the cemetery.

This integrative approach, which incorporates both geographic and sociocultural variables, provides a systematic framework for analysing burial ranking and the associated patterns of power and resource distribution within early complex societies.

The burial ranking shows a distinct social structure. Based on GIS grouping analysis, all 86 tombs can be classified into four hierarchical grades. Grade I includes six tombs, with all but one (M32, an early-stage tomb) belonging to the late stage. Grade II includes 32 tombs, the majority of which are from the early stage, except for three middle-stage tombs. Grade III includes 40 tombs: 24 from the early stage, 11 from the middle stage and five from the late stage. Grade IV includes eight tombs, of which two are early-stage and the remaining six are late-stage (Fig. 4).

**Grade I.** These tombs typically have a floor area greater than 4 square metres. They contain either a burial container and outer burial container or at least a burial container and have a second-tier platform on the east and west sides. Over 20 funerary objects are usually present, including numerous pottery vessels, finely crafted black thin-walled goblets, bone carving tubes, as well as jade artefacts and stone implements (such as axes) that symbolise social status and authority.

**Grade II.** These tombs generally have a floor area of ~2–3.5 square metres and contain a single burial container. The number of funerary objects typically exceeds 10, although only a few examples have more than 20. The assemblage commonly includes a variety of pottery vessels, along with a certain quantity of stone, bone, and shell artefacts. Decorative items may be present, though they are generally of lower quality or formality compared to those found in Grade I tombs.

**Grade III.** These tombs measure between 1.5 and 2 square metres in floor area and contain a single burial container. Fewer than ten funerary objects are typically present, mostly consisting of simple pottery, stone, bone and shell artefacts. The tomb occupants are presumed to be lower-status individuals from the common population.

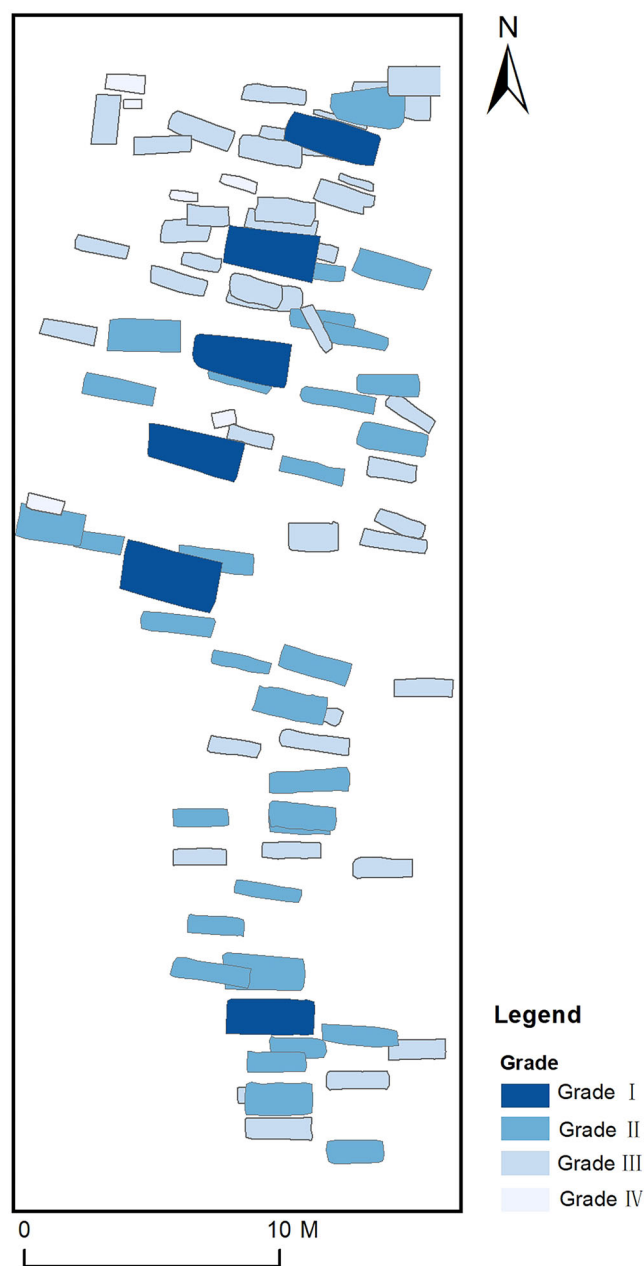
**Grade IV.** These tombs are less than 1.5 square metres in size and contain no burial furniture. The number of funerary objects does not exceed three, generally including only basic pottery, bone, or stone objects. The deceased are believed to be of very low status, possibly children, or individuals buried in ritual contexts, such as funeral murder.

From a diachronic perspective, the early-stage tombs in the northern zone of the Jiaojia cemetery were predominantly associated with the middle strata (Grade II and III). By the late stage, however, the proportion of high-ranking tombs (Grade I) increased, suggesting a trend toward the centralisation of social power and the entrenchment of hierarchical divisions. Meanwhile, the proportion of lower-ranking tombs remained consistently low, reflecting a degree of structural stability in the broader social hierarchy over time.

The results of the grouping analysis indicate an ‘olive-shaped’ social structure, with the middle tiers forming the majority: Grade II and III tombs together account for over 80% of the sample. These tombs typically contain basic funerary objects such as pottery and stone tools, along with a modest quantity of decorative items, reflecting the overall stability of social production and resource distribution.

Grade I tombs (~7%) are marked by their large scale, elaborate burial container structures, and high-prestige funerary objects, highlighting the symbolic authority and social prominence of the elite class. In contrast, Grade IV tombs (fewer than 10%) contain little to no funerary objects, possibly representing marginal individuals or socially peripheral groups.

Stage integration and grouping analysis further clarify social organisation. In the preceding analysis, tombs from different stages were integrated for hierarchical classification. However, as revealed by the Thiessen polygon analysis, the spatial distribution of late-stage tombs represents a

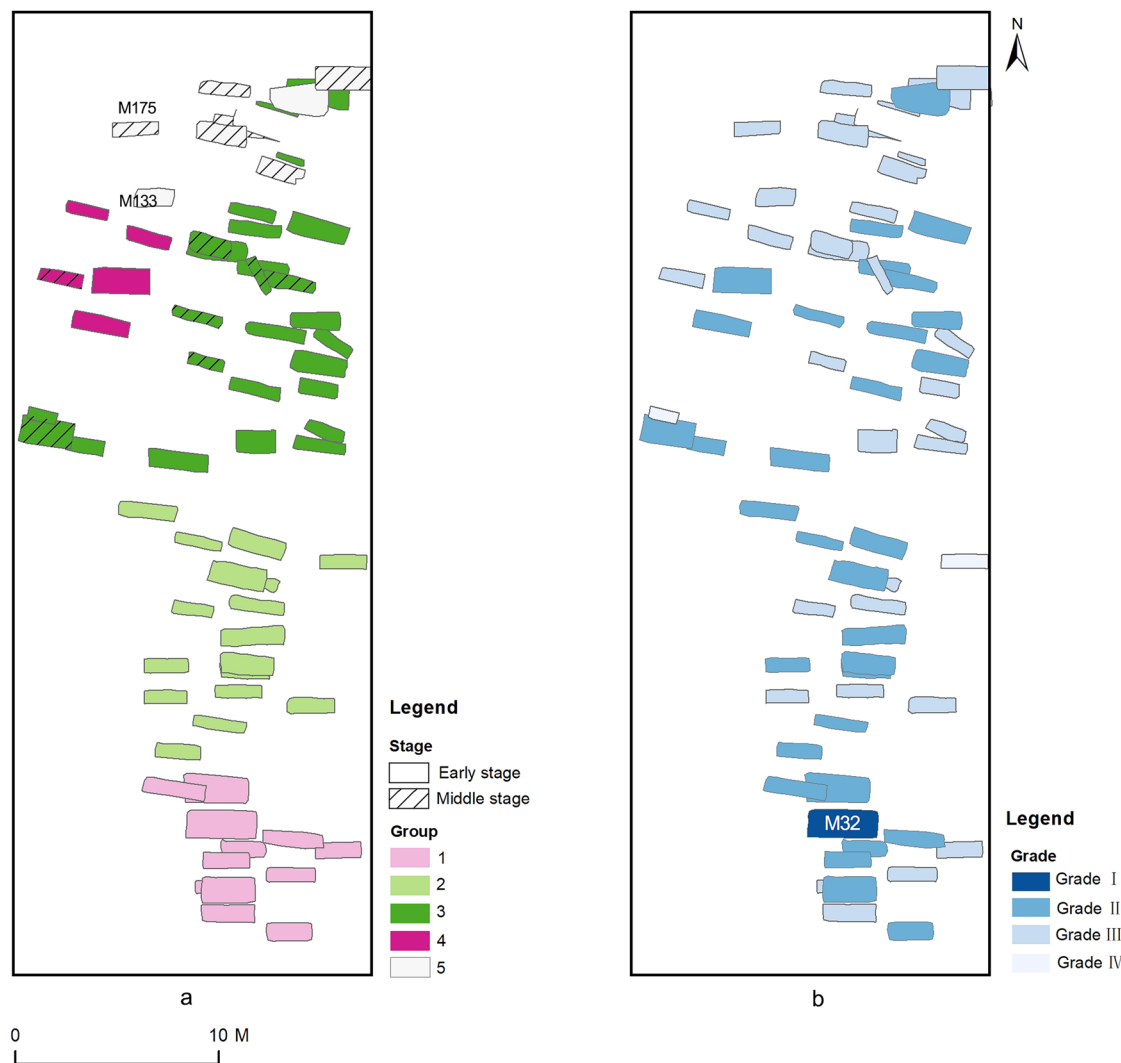


**Fig. 4** | Hierarchical classification of tombs.

reconfiguration of the cemetery’s layout, disrupting the relatively continuous and stable burial pattern observed during the early and middle stages. In light of this, the early- and middle-stage tombs will be treated as a unified group in the following analysis. A revised GIS-based grouping method will be applied to integrate spatial layout and hierarchical attribute data to further explore the internal structure of social stratification within the cemetery and its trajectory of transformation over time.

Based on GIS grouping analysis, a total of 70 early- and middle-stage tombs can be classified into four hierarchical grades and assigned to five spatial groups (Fig. 5).

From south to north, Group 1 corresponds exactly with Group Aa identified in the Thiessen polygon. It comprises 12 tombs, including one Grade I, seven Grade II, and four Grade III tombs. The spatial distribution exhibits a pattern in which lower-ranking tombs cluster around a central high-ranking tomb. Group 2 is fully consistent with Group Ab and includes 17 tombs—10 Grade II and seven Grade III. Group 3 partially corresponds to Groups Ba, Bb, Bc and Ca, totalling 27 tombs: 12 Grade II, 14 Grade III



**Fig. 5 | Stage integration and grouping. a** KNN-based grouping of early- and middle-stage tombs; **b** Hierarchical classification of early- and middle-stage tombs.

and one Grade IV. Group 4 largely overlaps with Group Ca and includes five tombs: two Grade II and three Grade III. Group 5 broadly corresponds to Group Bc. It contains eight tombs, including two with special samples. Tomb M133, while assigned to Ca in the Thiessen polygon, shows an orientation more closely aligned with Bc tombs. Moreover, the occupant of M133 was an adolescent, and juvenile burials were often placed near the peripheries of tomb groups or clusters, suggesting that this tomb may indeed belong to Bc. The case of M175 was discussed earlier and represents another special sample within this group.

The GIS-based grouping analysis, when combined with the results of the Thiessen polygon analysis, reveals the following characteristics of early- and middle-stage tombs:

First, correspondence between ranking and spatial grouping: The GIS grouping method divides the 70 tombs into five spatial groups and four grades, which correspond closely with the subdivisions identified through Thiessen polygon analysis.

Second, north–south differentiation in social stratification: In the southern core zone (Groups 1 and 2), higher-ranking tombs are more densely concentrated and exhibit a pronounced centripetal pattern. For instance, in Group 1, a central Group I tomb is surrounded by lower-ranking burials. Group 2 also demonstrates a stronger overall status, with Grade II tombs comprising 59% of the group. In contrast, the northern and peripheral zones (Groups 3, 4 and 5) show looser hierarchical structures and weaker centripetalism. Although Group 3 is the largest in scale, it is

dominated by Grade II and III tombs (96%) and exhibits a more dispersed spatial distribution, suggesting a tendency toward decentralised social organisation.

In summary, the strong consistency between the hierarchical clusters derived from GIS grouping and the spatial patterns revealed by Thiessen polygon analysis allows for a more accurate reconstruction of the cemetery’s socio-spatial structure. This integrated approach effectively identifies the southern core zone as the concentration of social power and the northern zone as its periphery. It also demonstrates the temporal continuity of social stratification during the early and middle stages while revealing a diachronic shift in the burial landscape from centralised core clustering to peripheral diffusion.

**The relationship between special funerary objects, burial customs and social organisation**

The relationship between special funerary objects (something is rare and exceptionally exquisite, e.g. fine pots, jade artefacts), burial customs and social organisation provides further insight. In early complex societies, special funerary objects and distinctive burial customs often corresponded to social stratification and mechanisms of power through three primary forms:

First, material expression of resource monopolisation: Tools, ritual vessels, or symbolic items made from rare materials (e.g. jade, ivory) are typically concentrated in a small number of tombs. Their acquisition often

relied on long-distance exchange networks or specialised labour, implying that elite groups exercised control over economic resources and craft technologies.

Second, hierarchical construction of ritual symbolism: Specific objects (such as ritual paraphernalia) or bodily modifications (e.g. tooth extraction, cranial deformation) served as standardised ritual symbols. Their forms and usage were monopolised by elites, reinforcing group identity while delineating social boundaries through restricted access to symbolic meaning and ritual authority.

Third, institutionalised narratives of power: Changes in burial modes—such as the shift from collective to nuclear family interments—as well as practices like human sacrifice reflect a transition in social organisation from kin-based communities to hierarchical structures.

The use of special funerary objects reflects elite control and restricted access to these items. With the accelerating process of social complexity, high-status special funerary objects increasingly became concentrated in large-scale tombs. The inclusion of these items as funerary offerings not only signified the elevated social identity of the deceased but also reflected the efforts of the deceased's kin group to renegotiate and restructure social relationships through the ritualised context of burial. In the Dawenkou culture, such funerary objects can generally be classified into three major categories: fine pottery, jade artefacts, and specific objects.

Painted pottery in the Haidai region during the middle to late phases of the Dawenkou culture was already in decline and does not appear to have been exclusively associated with elite groups. However, fine pottery was still found in medium- to large-scale tombs. In the study cemetery, the only Grade I tomb from the early stage—M32—yielded a painted pottery *beihu* (背壶, an asymmetrical lugged flask), which may be considered a status indicator for that period.

Both white pottery and black pottery appeared during Phase 8 of the Dawenkou period (corresponding to the middle stage in this study) and continued into the final stage of the culture, later being inherited by the Longshan culture. These two types of specific objects, emerging during a critical period of social stratification, have always been rare in number. Preliminary statistics based on current data show that nearly all white pottery and black pottery goblets with tall stems were excavated from large tombs, undoubtedly functioning as high-end consumer goods monopolised by the upper strata of Jiaojia society. In the northern zone of the Jiaojia cemetery, white pottery *gui* (鬲) vessels and black pottery goblets were exclusively found in five late-stage Grade I tombs. While these objects likely retained utilitarian functions, they were also imbued with ritual significance and symbolic value within the sociopolitical framework.

The frequent use of jade artefacts is one of the most notable features of the tombs in the Jiaojia cemetery. Among the 86 tombs analysed in this study, 44 (51.1%) tombs contain jade funerary objects in varying quantities. The jade items unearthed from this area can be broadly classified into ritual implements and decorations, with the former playing a more significant role in indicating the social rank of the deceased.

Since the early Dawenkou and Songze cultures, the *yue* (钺, similar to an axe) gradually became one of the most important forms of jade artefacts in prehistoric cultures of eastern China. During the period addressed in this study, finely crafted stone *yue* were commonly found in large tombs, especially those of males. These objects are generally interpreted as symbols of authority—likely functioning as ceremonial sceptres—representing both military power and elite social status. In our study, a total of 15 tombs yielded either stone axes or *yue*. Notably, only one of these (M40) belonged to a female and was classified as a Grade I tomb. This suggests that access to power in Jiaojia society was not strictly determined by gender; some women may have attained elite status through exceptional means such as military leadership, religious authority, or inheritance.

Although no jade *yue* have been discovered in the study Jiaojia cemetery, it is important to consider the widespread 'tomb destruction' observed in the five large late-stage tombs. It is possible that high-status funerary objects such as jade *yue* were looted or intentionally destroyed. Furthermore, both of the late-stage tombs that contained stone *yue* also yielded a

type of bone carving tube, likely used to decorate the butt end of the *yue* handle. The use of such finely crafted bone decorations would have further enhanced the ceremonial and symbolic nature of the *yue*.

Finally, there are other special objects, such as turtle-shell artefacts. Turtle-shell worship held considerable cultural significance in prehistoric eastern China and was particularly prevalent in the lower Yellow and Huai River regions, where the Haidai cultural sphere was located. Regarding the function of turtle-shell artefacts, most scholars associate them with shamanic or divinatory practices, attributing to them a form of primitive religious function. These items are typically interpreted as talismanic objects worn by the deceased during their lifetime.

In the study cemetery, only tomb M78 yielded a turtle-shell artefact. The tomb belonged to a young adult male and was classified as a Grade III (medium-sized) burial. Similarly, turtle-shell artefacts at other contemporary Dawenkou sites were also more commonly found in middle-tier burials. Some scholars argue that this pattern may reflect the social status of the individuals who wore such items—although they were not part of the ruling elite or tribal leadership, they likely held positions above those of ordinary members of society<sup>45</sup>.

The prevalence of specific burial customs shows distinct social and temporal patterns. Common special burial customs in the Jiaojia cemetery include tooth extraction and the inclusion of roe deer teeth as funerary objects. Additionally, a small number of adolescent burials located near large tombs may represent instances of human sacrifice.

The practice of tooth extraction was a distinctive custom among prehistoric populations in the Haidai region, particularly those of the Dawenkou Culture. Based on the high frequency of this practice—especially the consistent removal of both maxillary lateral incisors—and its occurrence at around the age of sexual maturity (~15 years old), some scholars have interpreted it as a form of initiation rite marking adulthood and readiness for marriage<sup>46</sup>.

In the study cemetery, a total of 43 tombs (50% of the sample) exhibit evidence of tooth extraction. Chronologically, the proportion of such tombs decreases markedly from early to late stage, with 57% in the early stage, 50% in the middle and only 25% in the late stage. This decline indicates that the practice of tooth extraction gradually diminished over time, a pattern consistent with broader regional trends observed across the Haidai region.

Spatially, these burials are primarily concentrated within Groups A and B, as identified in the previous Thiessen polygon analysis. In terms of gender, among the individuals with identifiable sex, 19 male and 23 female burials showed evidence of extracted teeth, suggesting no significant gender-based difference in the practice (Fig. 6).

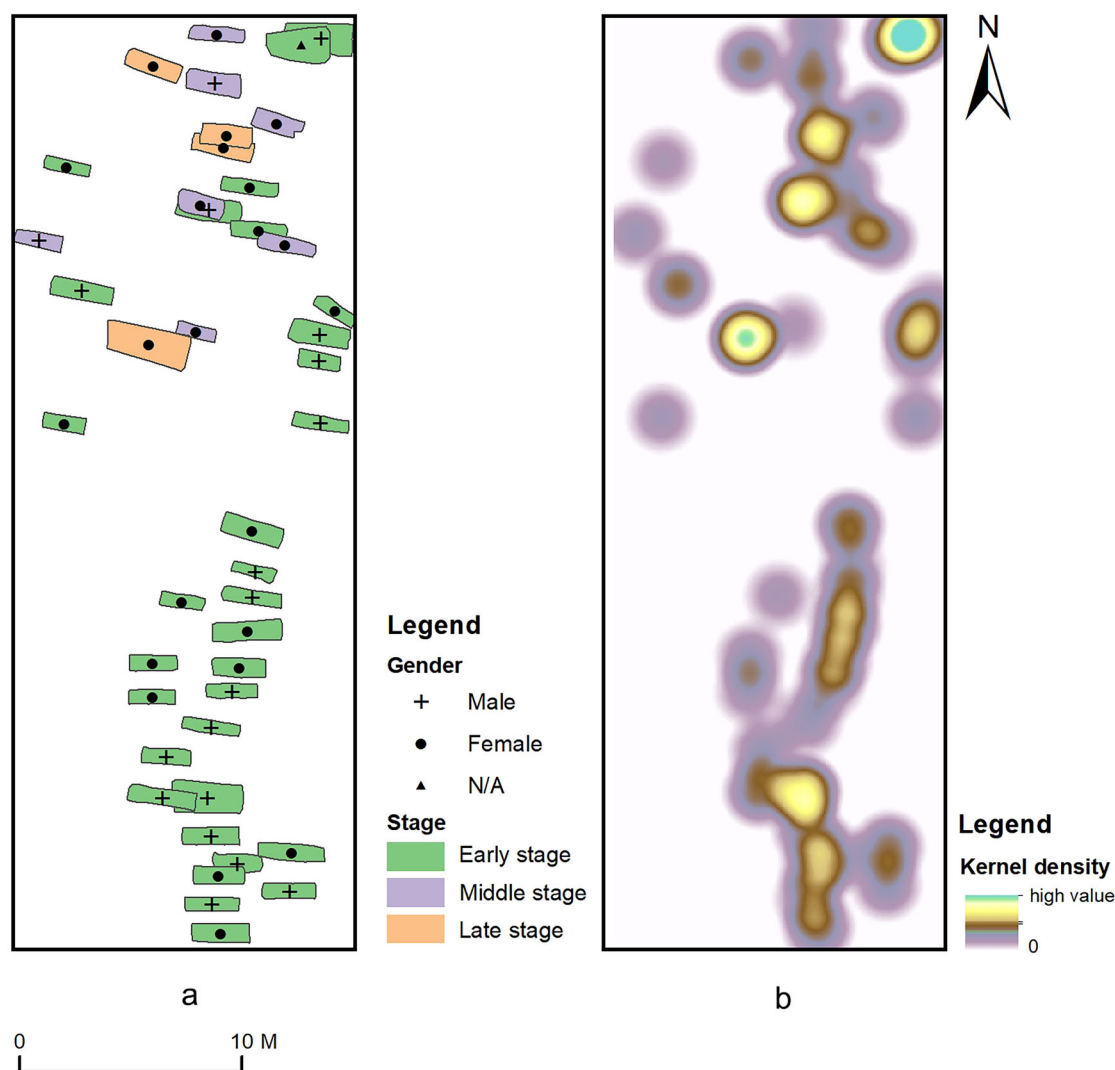
Temporally, the custom of including roe deer teeth as funerary objects was widespread from the early to late stages of the Dawenkou Culture and, at some sites, even continued into the Longshan period.

The inclusion of roe deer teeth in burials may have originated from totemic worship of roe deer among Dawenkou communities. Some studies also suggest a possible connection between this custom and the tooth extraction.

A total of 23 tombs in the study cemetery contain roe deer teeth as funerary objects, indicating that this custom was less prevalent than tooth extraction. Chronologically, the proportion of such burials declines over time, with 30% in the early stage, 21% in the middle and 19% in the late stage—reflecting a trend similar to that observed in the practice of tooth extraction.

Spatially, the distribution of these burials is generally sparse and scattered, with only a modest degree of concentration in the northeastern portion of the cemetery. Regarding gender, among the burials with identifiable sex, two males and 19 females were buried with roe deer teeth, demonstrating a notable gender disparity in the practice (Fig. 7).

Furthermore, funeral murder also merits attention. To the west of two high-ranking late-stage tombs, M20 and M40, lies a cluster of juvenile burials, including M2, M5, M9, M11 and M54. These tombs exhibit consistent orientation, shallow burial pits, and few or no funerary objects.



**Fig. 6 | Spatial distribution of tooth extraction burials. a** Distribution of burials by stage and sex; **b** Kernel density map of tooth extraction burials.

M2 individual's hands covering the face, accompanied by pig mandible and teeth. No systematically arranged funerary objects were found in M11, though four items were scattered in the fill near the skeletal remains. M5 is a single burial in a lateral flexed position with face covered, accompanied by a pig mandible and pig teeth. No other funerary objects were found. The burial posture—hand covering the face—suggests the possibility of live interment leading to death. M9, the burial of a child, shows severe cranial fragmentation; the left leg is broken at the mid-tibia, and the right leg at the proximal tibia, with the feet missing. These signs suggest the possibility of funeral murder. M54 is a flexed supine burial with poorly preserved skeletal remains.

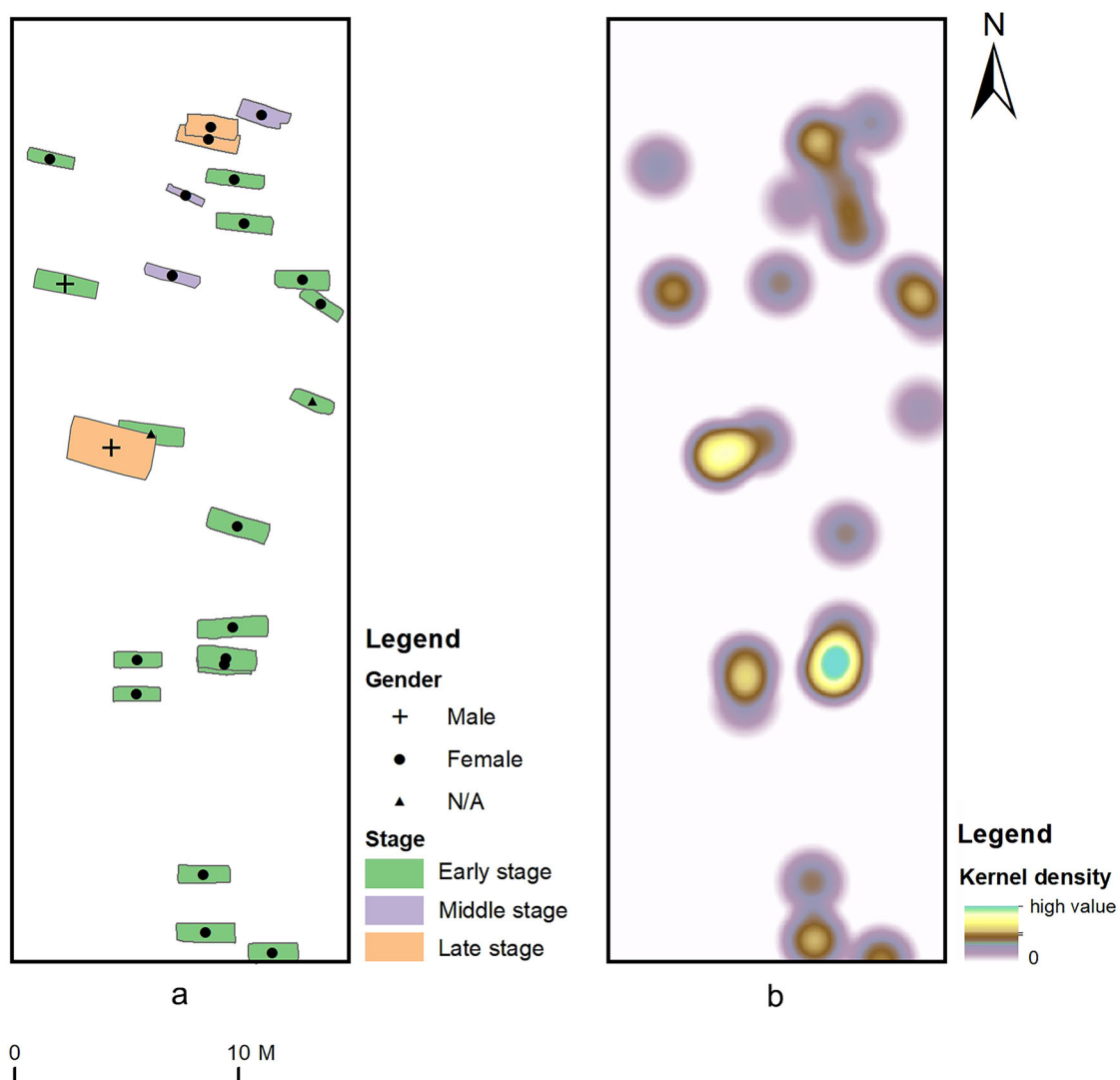
This area was likely a deliberately planned juvenile burial zone. Given the spatial proximity to elite tombs and the distinctive burial features, it is plausible that these individuals were victims of funeral murder associated with high-ranking mortuary rituals.

### Discussion

This study focuses on the Jiaojia site, a regional centre settlement from the middle to late Dawenkou culture and the earliest prehistoric urban site in the lower Yellow River basin. Centered on the 2016 excavation area, an integrated analysis was conducted on 86 tombs in the northern cemetery zone. By systematically applying GIS spatial analysis methods (including Thiessen polygons, KDE, and spatial constraint), alongside traditional tomb morphology and social stratification theories, this research establishes an

analytical framework intertwining spatial, temporal and social dimensions. It offers an in-depth investigation of the internal organisational structure and diachronic changes in social stratification within the cemetery, as well as the broader implications for cultural changes. Our main findings can be summarised in four aspects.

First, from a spatial perspective, the layout of the northern cemetery at Jiaojia exhibits a clear diachronic trajectory. During the early stage, tombs were widely distributed, forming three major groups (A, B, C) and seven subgroups. Thiessen polygon analysis reveals a hierarchical internal structure characterised by dense central areas and sparse edges within these groups. Combined with considerable variation in tomb orientations, this strongly indicates that the social organisation at the time consisted of multiple relatively independent yet coexisting communities, likely based on kinship or clan affiliations. In the middle stage, tomb numbers sharply decreased and concentrated in the northern half of the cemetery. A key spatial finding is that these seemingly scattered tombs precisely filled the vacant spaces left by the early-stage tombs without overlapping or disrupting them. This spatial distribution pattern demonstrates continuity and expansion of the earlier established cemetery framework, reflecting the inheritance of social structure and the stability of social memory. However, by the late stage, the spatial pattern underwent a drastic transformation. The continuous spatial framework established earlier was broken, replaced by a bipolar structure: an eastern elite cemetery row consisting of five large tombs (M40, M20, M6, M90 and M17) arranged in a carefully planned



**Fig. 7 | Spatial distribution of burials with roe deer teeth. a** Distribution of burials by stage and sex; **b** Kernel density map of burials with roe deer teeth.

north–south alignment with uniform spacing, and a northwestern cluster of nine minor tombs, some with special burial forms. This spatial polarisation and institutionalised zoning indicate that power forms had transcended the earlier autonomous kin-based model, moving toward institutionalisation and planned organisation, with social stratification strongly manifested spatially.

Second, the results of social stratification analysis align closely with the conclusions drawn from spatial changes. By applying spatially constrained clustering based on tomb locations and core attributes, the hierarchical structure and its transformation within Jiaojia society are reconstructed. Overall, Jiaojia exhibits a stable ‘olive-shaped’ social structure: mid-level strata (Grades II and III) account for over 80% and form the societal base, while top-tier (Grade I) and bottom-tier (Grade IV) tombs account for ~7 and 10%, respectively, occupying the two ends of the social spectrum. Spatial clustering further reveals that two groups in the southern sector (Group A in the Thiessen polygon analysis) constitute the core power zone, characterised by a dense and centripetal distribution of high-level tombs and high resource concentration. In contrast, northern groups display a looser stratification, suggesting their status as secondary centres or peripheral communities. The most striking shift occurs in the late stage: nearly all first-tier tombs appear during this stage, and their deliberate spatial planning serves as a symbolic declaration of social status and hereditary authority. Meanwhile, the cluster of juvenile tombs concentrated in the northwest strongly suggests the practice of funeral murder, based on both location and burial

features. This shift marks a transition from relatively fluid early social hierarchies to the institutionalisation, ossification, and possible heritability of social status in the late stage, with a pronounced trend toward centralised and monopolised power.

Third, the analysis of specific funerary objects and mortuary practices provides micro-level evidence for understanding social differentiation and ideology. High-end resources were strictly monopolised and ritualised by the social elite: white pottery *gui* and black pottery goblets with high stems emerged as objects exclusive to the five large tombs of the late stage. *Yue* and their accompanying bone carving tubes, symbols of military or religious authority, were concentrated in medium- and large-sized tombs. These luxury items—reliant on long-distance trade or specialised craft systems—reflect the elite’s control over economic resources, production technologies, and the interpretation of ritual symbols. This pattern exemplifies the core mechanisms of social complexity: the maturation of resource redistribution and ideological control. In stark contrast, traditional mortuary customs experienced a notable decline. Customs such as tooth extraction—possibly a coming-of-age rite signalling community identity—and the funerary with roe deer teeth—likely linked to totemic worship—diminished over time. This decline appears closely tied to the broader transformation of social structure in the late stage. As the power of core lineages or noble groups became institutionalised, they likely promoted a new ideology—expressed through exclusive funerary ‘ritual systems’—that gradually replaced or weakened traditional rites rooted in kin-based communal identities. This

shift highlights a profound transformation in mechanisms of social integration and control.

Fourth, from a methodological perspective, this study systematically expands the depth of GIS applications in cemetery archaeology. By incorporating tomb chamber area and orientation as weighted factors in the Thiessen polygon analysis, the study effectively overcomes the homogenising limitations of traditional methods that neglect attribute information. This significantly enhances the accuracy in identifying patterns of multi-community coexistence. Furthermore, the innovative introduction of a spatial-attribute dual-constraint clustering model (based on the KNN model) successfully quantifies the relationship between tomb location and social ranking attributes. This approach offers a new case study for extracting information on social organisation and hierarchy from the spatial distribution of archaeological remains.

In summary, the study demonstrates that the late phase of the Dawenkou culture marked a critical period of sociopolitical transformation in the Haidai region. As an emerging regional centre at the time, Jiaojia exhibited a cemetery layout that evolved from early-stage multi-group cohabitation, through middle-stage spatial continuity, to late-stage institutionalised hierarchy and exclusive spatial zoning. Social structure transitioned from a stable ‘olive-shaped’ model—dominated by middle-ranking groups—to a late-stage configuration characterised by concentrated elite power and a potentially fixed class of lower-status dependents. In terms of material culture, the elite monopolised luxury goods and initiated the ritual use of ritual vessels, while older identity-related customs declined. Collectively, these shifts indicate that by the late Dawenkou period, Jiaojia society was transitioning from an egalitarian or stratified kin-based organisation toward a more centralised, hierarchical, and institutionalised form of complex society.

This study also has certain limitations. The Thiessen polygon method, while effective in identifying spatial structure, remains static in capturing dynamic social change. Kernel density analysis is constrained by sample size and thus limited in interpretive power. The identification of special individuals (such as possible ‘non-locals’ M47 and M175) still lacks bioarchaeological corroboration. In addition, the widespread destruction of tombs in the late stage has interfered with the evaluation of high-status ritual object assemblages such as jade artefacts. Future research could incorporate scientific techniques such as ancient DNA and strontium isotope analysis to trace population mobility and further explore the relationship between cemeteries and broader site functions (e.g. residential zones, city walls, and ritual areas) to better understand the driving mechanisms behind the civilisation process.

### Data availability

The datasets analysed during the current study are not publicly available owing to the confidential nature of archaeological excavations, but are available from the corresponding author on reasonable request.

### Code availability

Not applicable.

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### Author contributions

Z.L. and Q.M. made significant contributions to the study equally, including manuscript writing, result discussion, and manuscript editing. X.L. worked on collecting and verifying the datasets. Z.F. participated in the production of figures. F.W. provided the conceptual framework, Z.T. and H.W. edited the manuscript. All authors reviewed the manuscript.

### Competing interests

The authors declare no competing interests.

### Additional information

**Correspondence** and requests for materials should be addressed to Zhongming Tang or Hao Wu.

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