Spherical harmonic analysis of faceted spheroids identifies shaping strategies and standardisation at Qianshangying (North China)

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Abstract

Text of abstract

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# Introduction

Spheroids are a widely distributed type of stone artifact, appearing across a broad temporal and geographic range, from the Oldowan and Acheulean to the Middle Paleolithic, and in diverse archaeological assemblages(Cabanès et al., 2024; Willoughby, 1985). Initially, Clark (1955) was the pioneer to conduct the study of archaeological stone balls. Then Kleindienst (1962) proposed the description of missile, polyhedron and bola. After that, the terminology of spheroid and subspheroid was formally introduced by Leakey (1971) in his classification of the Developed Oldowan. At present, commonly used definitions of ball-like stone artifacts are as follows: spheroids are rounded lithic objects whose entire surface is covered with flake scars, while subspheroids are generally less symmetrical and may retain portions of the original cortex. Compared to spheroids, polyhedrons are characterized by multiple intersecting flake removals, producing a distinctly angular morphology; bolas exhibit smoother and more rounded surfaces with no visible crests (De Weyer, 2017; Leakey, 1971; Titton et al., 2020).

These stone balls are frequently grouped under the category “PSB” of Polyhedron, Spheroid and Bola (or “PSSB” when subspheroids are included) and are commonly interpreted as volumetrically reduced artifacts organized around a central point. This morphology-based classification has been widely accepted, but it has led to challenges. Research has shown that these forms may not represent a continuous *chaîne opératoire*: differences in raw material selection suggest divergent technological strategies and potentially distinct functional purposes (De Weyer, 2017; Jones et al., 1994). This illustrates the limitations of typology in the classification and study of stone artifacts, as it is overly reliant on morphology. There is a need to establish new criteria to distinguish these artifacts and to determine their respective production purposes and strategies, if such purposes and strategies exist.

At present, the technological category and function of spheroids remain central topics of debate. Broadly, spheroids have been interpreted as cores (Sahnouni et al., 1997), projectiles (Leakey, 1979), and hammerstones (Mussi, 2025; Schick and Toth, 1994), or a specialized tool for working animal bones (Assaf et al., 2025). Closely tied to this debate is the question of their production strategy, which remains unclear. Experimental replication and site-specific diacritical analyses have produced divergent interpretations. One view suggests that spheroids emerged unintentionally as the by-products of core exhaustion, which represents a low-effort strategy aimed at flake production (Sahnouni et al., 1997). Another perspective holds that spheroids were unconsciously produced through high-intensity battering (Clark, 1955; Mora and De La Torre, 2005; Schick and Toth, 1994). In contrast, a third view proposes that spheroids reflect a conceptual template and were produced through a deliberate shaping strategy (Muller et al., 2023; Texier and Roche, 2014; Titton et al., 2020).

This debate remains stalled for several reasons. Typological studies relied heavily on researchers’ observations and experiential judgments, which lack objectivity. Some experiments attempted to demonstrate whether spheroids were intentionally or unintentionally produced, yet the researchers involved tend to introduce bias, making it impossible to achieve truly “unconscious” production. In addition, from an objective perspective, most studies can only reflect the characteristics of spheroids from a specific region or site, whereas spheroids themselves display considerable diversity in aspects such as raw materials and surface features. Also, conclusions drawn from their own analyses are rarely subject to external validation or replication. As a result, both the research methods and the inherent diversity of spheroids have hindered the advancement of in-depth studies on spheroids.

To address these challenges, we developed a set of quantitative methods that integrate morphological and technological analyses to investigate spheroid production strategies. While previous morphological measures have focused on the shape of spheroids close to perfect sphere, contributing to discussions of spheroid standardization, they provided limited assistance in reflecting on production strategies. We therefore adopted spherical harmonics, a landmark-free method recently introduced to archaeology. This offers morphometric precision comparable to geometric morphometrics but does not rely on predefined landmarks, making it particularly suitable for artifacts like spheroids that lack homologous landmarks. We introduce a novel modification of the spherical harmonics method to distinguish the morphological variability of flaked pieces, enabling us to differentiate between spheroids and multifacial cores or polyhedrons. To our knowledge, this is the first attempt of its kind in the field of archaeology. Additional technological analyses, including flake scar orientation analysis and reduction index calculation, further contribute to reconstructing the spheroid production process. All of the methods we present here are open-source to enable replication of our results and support unified, cross-regional quantitative studies in the future .

We demonstrate these methods in a case study of spheroids recovered from the recently excavated site of Qianshangying in the Nihewan Basin of Northern China. In the following sections, we assess whether the Qianshangying spheroids exhibit a patterned production process and standardized morphology, if so, the conceptual template and specialized production intention can be proven. We adopt a comparative approach, comparing spheroids with polyhedrons and multifacial cores. Our comparative study serves two purposes: first, to test whether spheroids follow a distinct production sequence, and second, to explore the potential, beyond typological approaches, of using quantitative methods to distinguish spheroids from cores subjected to intensive reduction. Further, we situated the Middle Pleistocene Qianshangying site within the broader context of East Asia to explore the technological behaviors and cultural traditions associated with spheroid production, also providing one of the first contributions to understanding the spatial and temporal distribution of spheroids in this region. Most importantly, we offer an efficient and transparent framework combining morphological and technological analyses, enabling comparative studies of spheroid production strategies across regions and archaeological sites.

# Qianshangying and its spheroids

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| Figure 1: Geological Context and Chrono-Stratigraphy of the QSY Site) |

The Qianshangying site complex lies in the Nihewan Basin, a region in northern China situated between the Chinese Loess Plateau and the Inner Mongolian Plateau. The basin preserves extensive Quaternary fluvio-lacustrine and loess deposits (Barbour et al., 1926; Deng et al., 2008; Li et al., 2000; Yuan et al., 2009a), hosts the highest concentrations of Pleistocene Paleolithic sites in East Asia, and is especially significant for preserving evidence of early hominin activities outside Africa dating back over one million years (Pei et al., 2019, 2017; Yang et al., 2020, 2017; Zhu et al., 2004, 2001). In recent years, nearly 20 Middle Pleistocene sites—including Jijiazhuang and Caijiagou—have been identified in the southeastern part of the basin (Du et al., 2023; Pei et al., 2018; Ye et al., 2024), within the Yuxian Sub-basin, resulting in a long and detailed regional cultural sequence for the Nihewan Basin ([Figure 1](#fig-QSY-geography-chronology)).

The Qianshangying site complex consists of four localities from QSY-A to QSY-D, discovered in 2015. It is among the region’s most artifact-rich archaeological site. Geomorphological and sedimentological evidence indicates that the stratigraphy at the site records a full cycle of lake expansion, retreat, re-expansion, and eventually disappearance of the ancient Nihewan lake, and hominin occupation occurred in a marginal lacustrine setting during a low lake-level episode (Deng et al., 2008; Li, 2020; Z. Ye et al., 2025; Ye et al., 2024; Yuan et al., 2009b; Zhou et al., 1991). The stratigraphic context of Qianshangying indicates a short-term occupation resulting from a single hominin activity event. Analyses of artefact orientations and size distributions indicates that the assemblage appears to be largely *in situ*, exhibiting minimal disturbance after deposition (Z. Ye et al., 2025). ESR dating of the cultural layer places hominin activity at approximately 429 ± 39 ka (Z. Ye et al., 2025).

A total of 956 stone artifacts were recovered from four localities at Qianshangying. Following a widely used techno-typological framework (De La Torre, 2004; G. L. Isaac, 1986, 1981; Pei et al., 2017; Torre and Mora, 2018), the assemblage was classified into four general categories: flaked pieces (n = 248, 26.0%), detached pieces (n = 686, 71.8%), pounded pieces (n = 4, 0.4%), and unmodified materials (n = 17, 1.8%). Among these, 6 spheroids and 7 subspheroids were identified; together forming a spheroid group of 13 pieces, accounting for 1.3% of the total lithic assemblage. They are all faceted spheroids with intensive flake scars on the surface. Employing typological criteria to identify spheroids at this stage is not inherently mistaken, as we later validate this classification through quantitative analyses, with the goal of developing new standards.

Raw materials at Qianshangying were classified into four categories following Pei and Hou (2002) and Pei et al. (2017): lava, dolomite, chert, and others. The overall assemblage is dominated by lava ( n = 637, 66.7% ), followed by dolomite ( n = 209, 21.9% ), with smaller proportions of chert ( n = 53, 5.5% ) and other materials ( n = 56, 5.9% ). The composition of cores closely mirrors this distribution, among them, polyhedrons and multifacial cores show higher frequency on chert ( n = 3, 10.3% ) and lower frequency on dolomite ( n = 5, 17.2% ). In contrast, spheroids and subspheroids exhibit a marked preference for lava (n = 11, 84.6%), with reduced use of siliceous dolomite ( n = 2, 15.4% ) and no use of chert. Compared to the cores, spheroids and subspheroids show a stronger reliance on lava and a diminished use of more fragile materials, suggesting a selective strategy favoring raw materials with more stable and homogeneous physical properties.

In terms of dimensions, the average length, width, thickness, and mass of spheroids subspheroids were 84 mm (SD = 35.9), 69.8 mm (SD = 23.4), 61.2 mm (SD = 21.1), and 644.6 g (SD = 727.5), respectively, as shown in [Figure 2](#fig-basic-characteristics). few spheroids showed outlier values in size, being either unusually large or small, while the rest exhibited relatively concentrated size distributions. In contrast, polyhedrons and multifacial cores displayed greater variability in size, with standard deviations of 27.4 mm, 26.1 mm, and 22.1 mm for length, width, and thickness, respectively. Additionally, spheroids tend to have similar values across length, width, and thickness, reflecting their overall symmetry. Polyhedrons and multifacial cores show marked differences among these dimensions, indicating more irregular and elongated forms.

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| Figure 2: Basic characteristics of the Qianshangying assemblage. A: Raw material proportions. B: Box plot comparing of core, spheroid, and multifacial core dimensions |

# Method

We generated 3D models of the cores for morphometric and technological analysis. Digital data were captured using Artec Spider, and post-processing was carried out with Artec Studio 18. The 3D scan files and all the R and Python code used in the analyses reported here are openly available online at https://doi.org/xxxx/xxxx/xxxx/.

## Morphometric Analysis

In our typological study, we used quantitative methods including the sphericity index, 3D spherical harmonics, and spherical harmonic energy (SHE) to show the shape features of spheroids. We also examined the degree of standardization of the spheroids by computing coefficients of variation (Eerkens and Bettinger, 2001; Muller and Clarkson, 2023) of shape proxies. Furthermore, we compared the results of the typological classification and our new morphometric analyses.

### Sphericity index

To evaluate the degree to which the artifacts approximate a perfect sphere, we employed a standardized sphericity index originally proposed by Wadell (1935) and later adapted for 3D digital models in geoscientific research. The index is calculated using the following function:

Where V is the volume and A is the surface area of the object. This dimensionless metric yields a maximum value of 1 for a perfect sphere. While values closer to 1 generally indicate a more spherical geometry, sphericity is calculated solely from volume and surface area. As a result, some irregular objects may exhibit high sphericity, while conversely, objects that are generally spherical in shape may deviate from ideal sphericity due to surface roughness. Thus, sphericity serves as a useful but limited proxy for assessing how close an object is to a perfect sphere. We used Python to decimate to a consistent face count from our 3D scan files and conduct a unit normalization to ensure comparability across artifacts, and then derived surface area and volume measurements from these processed 3D mesh models.

### 3D spherical harmonics analysis

Spherical Harmonic (SPHARM) analysis is a method for describing 3D shapes using a series of mathematical functions defined on the surface of a sphere. It works like a 3D version of Fourier analysis, breaking down complex shapes into components of different spatial frequencies. Each shape is first mapped onto a unit sphere and then expressed as a combination of spherical harmonic basis functions according to

where the set of coefficients quantifies how much each basis function contributes to the overall shape. Here, θ and ϕ are angles in spherical coordinates, l and m are order and degree respectively. Lower-order terms describe the general shape, while higher-order terms capture finer details ([Figure 6](#fig-SPHARM-Reconstruction-by-Degree)).

This method has been widely used in the field of biology, for example in the analysis of skull and cell morphology (Grieb et al., 2022; Harper et al., 2022; Hewitt et al., 2024; Link et al., 2024; Medyukhina et al., 2020). However, there have been very few applications of SPHARM to archaeological artifacts. Sholts et al. (2017) applied SPHARM-PDM to standardize the number and position of vertices across early North American bifaces (ca 13,100–9,000 BP), enabling point-by-point comparison of original and mirrored shapes to assess asymmetry variation, but SPHARM was not directly used to describe stone tool shape. Muller et al. (2023) used closed-source and proprietary Matlab software to investigate intentionality in the production of 150 spheroids from ’Ubeidiya (ca 1.4 Ma) in the Levant. Muller et al. (2023) did not provide code to document their analysis, but they found that lithic reduction resulted in the spheroids becoming more spherical, and concluded that spheroids represent intentionally knapped items. Noshita et al. (2025) used 3D Slicer-SlicerSALT to apply spherical harmonic analysis to Ongagawa-style pottery in the Yayoi period of Japan (800 BC–AD 250). Their results were consistent with the hypothesis of an association of Ongagawa-style pottery with the spread of agriculture via two routes in prehistoric Japan, and they provided code and date files to enable their analysis to be reproduced.

Our work combines the merits of these previous studies to demonstrate an open-source and reproducible analysis of stone artefacts using SPHARM. We further introduce the use of rotation-invariant power spectrum and UMAP to extract shape features, explore hidden structures in data, and then achieve grouping among spheroids and cores, marking a first in archaeological research while significantly extending the depth of analysis provided by SPHARM. All these steps were completed in Python. We hope to demonstrate the value of this method for quantitative shape analyses of objects that are roughly spherical in shape, such as the spheroids and cores in our case study from Qianshangying.

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| Figure 3: Schematic summary of the key steps of 3D spherical harmonics analysis. a. UMAP on SPHARM power spectrum for the dimensionality reduction and data structure analysis; b. Spherical harmonics energy (SHE) derived from the SPHARM power spectrum to evaluate the similarity between shapes and the perfect sphere |

As shown in the [Figure 3](#fig-SPHARM-steps), following the approach by Medyukhina et al. (2020) and Link et al. (2024), we first imported, cleaned, simplified and normalized the STL files of spheroids and cores to obtain 3D mesh vertices, which were then converted from Cartesian (x, y, z) to spherical coordinates (r, θ, φ). Next, we interpolated radial values onto a regular spherical grid of N×N and then decomposed them using spherical harmonics based on the Driscoll–Healy sampling scheme (Wieczorek and Meschede, 2018). The resulting coefficients were normalized for scale-invariant comparison across models.

From the normalized spherical harmonic coefficients, we computed the rotation-invariant power spectrum by summing the squared magnitudes of the coefficients at each degree. Each 3D shape is thus represented by its unique power spectrum, which serves as a multidimensional descriptor. To explore relationships between models, we applied a Uniform Manifold Approximation and Projection (UMAP) for dimensionality reduction and visualization (Bavel et al., 2023). Unlike traditional linear dimensionality reduction methods such as Principal Component Analysis (PCA), which capture only global linear variance patterns and typically rely on the first few spherical harmonic coefficients, UMAP is a non-linear technique designed to preserve both local and global data structure. Its grouping is based on the local and global similarity of shape data. This makes UMAP particularly well suited for complex shape data represented by spherical harmonic power spectrum, where morphological variations may manifest in subtle, non-linear ways across multiple degrees. By effectively capturing these non-linear relationships, UMAP yields a refined morphospace representation, enabling detection of complex shape differences that linear techniques may overlook.

To assist in the interpretation of the groupings revealed by UMAP, we included a set of standard geometric models—sphere, rounded cube, ellipsoid (1.2:1:0.8), rounded box (1.2:1:1), and disc-like forms (flattened and discoid core)—in the SPHARM analysis and UMAP embedding as visual references. Spheroids, polyhedrons and multifacial cores were positioned in this morphospace based on their morphological similarity to these reference models: individuals that cluster more closely to a specific standard form exhibit corresponding shape characteristics.

### Spherical Harmonic Energy

Additionally, we computed the spherical harmonic energy (SHE), defined as the sum of squared normalized spherical harmonic coefficients for each degree. This provides a rotation-invariant measure of overall shape complexity and surface regularity. For normalized shapes, this total energy approaches a value of one for a perfect sphere, while more irregular shapes yield higher values.

Notably, classic sphericity metrics (Wadell, 1935) exhibit critical limitations in differentiating morphotypes with equivalent surface-area-to-volume ratios. SHE overcomes this constraint through spherical harmonic decomposition of surface morphology, and this allows it to distinguish localized irregularities (like core edge or concave) from global shape deviations (e.g., elongation)-differences that classic sphericity metrics often fail to capture.

We computed the total energy at degree 20, a resolution high enough to capture surface details. Lower energy values indicate more regular or rounded surfaces, while higher values reflect more irregular or angular geometries.

## Technological Analysis

We applied technological analysis of the production strategies of spheroids in Qianshangying. Together these methods help determine whether the artifacts were intentionally shaped and whether their manufacture followed standardized procedures. Addressing this question is crucial for achieving our goal of determining whether or not spheroids represent a distinct technological category, separate from exhausted cores.

### Diacritical analysis

We used diacritical analysis to reconstruct the reduction sequence based on superimposition relationships among scars on spheroids (Cabanès et al., 2024; Titton et al., 2020). This method enables the identification of the order of scar removal, allowing us to understand the organization of removals. All spheroids were included in the analysis to assess whether removal organization differs systematically from the group of polyhedrons and multifacial cores.

Following the reconstruction of reduction sequences, we adopted an inductive approach to infer exploitation models of spheroids, that is, the removal patterns and associated stages employed in a spheroid. Our goal was to reconstruct the complete chaîne opératoire of spheroids, from the selection of raw material and initial blank to the final product. If consistent patterns can be observed, they may indicate shared reduction schemes or conceptual templates. We also explored whether multifacial cores and polyhedrons may represent earlier stages in spheroid reduction sequences, contributing to understanding the technological relationship between these types.

### Orientation analysis

To further investigate technological strategies, we incorporated orientation statistics as a complementary approach. This method derives from fabric analysis originally used in sedimentology and has since been adapted to study the arrangement of flake scars on lithic artifacts. We followed the protocol developed by Lin (2024). In our study, only those scars with a length greater than 5mm were recorded, after extracting scar vectors from each samples and calculating eigenvalues we computed the isotropic ratio and elongation ratio and visualized the result in a ternary plot. These steps were carried out in Geomagic Wrap 2021, Rhino8 and R 4.4.3 and documented in Zhi Ye et al. (2025).

Results were visualized using ternary plots to compare orientation statistics between spheroids and other core types. Based on our hypothesis, if spheroids were shaped following a consistent reduction sequence, they should exhibit similar and patterned orientation results. In contrast, if they merely represented exhausted cores, the orientation patterns would appear random and highly variable, similar to those of undirected polyhedron and multifacial cores.

## Efficiency of shaping strategy

The following group of methods aims to investigate how the morphology of spheroids changed during the reduction process. We hypothesize that as reduction intensity increases, spheroids will progressively approximate a perfect sphere. This would indicate a high-efficiency shaping strategy, where each step is directed toward achieving a predefined morphological goal. To test this hypothesis, we established a set of quantitative indicators for reduction intensity and spheroid morphology.

### Degree of reduction

To compute the degree of reduction we collected data on three metrics: scar number, removal ratio and scar density index (SDI). We measured scar number as total number of flake scars visible on the spheroid surface. Removal ratio was calculated as 1 minus cortex ratio, where the cortex ratio represents the proportion of cortical surface area to total surface area (Cabanès et al., 2024). We used the removal ratio instead of the traditional cortex ratio in order to maintain a positive correlation with other reduction intensity indicators. The scar density index (SDI), defined as the number of flake scars divided by the total surface area, serves as a robust indicator of core reduction intensity, effectively capturing the dynamic nature of the reduction process (following Clarkson (2013)). In all three metrics, higher values represent more advanced stages of reduction. Scar counts and surface area measurements were extracted using Geomagic Wrap.

### Spheroid shape

We measured spheroid shape with four metrics: sphericity, and spherical harmonic energy (SHE), along with mean edge angle, mean surface curvature. To assess mean edge angle, ten edge intersections were randomly sampled on each spheroid, and edge angles were calculated following (**tittonSubspheroidsLithicAssemblage2020by?**) constructing triangles at ridge intersections, extracting vertex coordinates in Geomagic Wrap, and computing the angles from these coordinates using trigonometric functions in R. Higher mean edge angles indicate a more spherical geometry. We estimated local curvature for each triangular face of the 3D mesh model using a k-nearest neighbors approach in Python. For each triangle, a best-fit plane was fitted to its neighboring triangle centers, and the angle between the triangle’s normal and the best-fit plane’s normal was computed. The average of these angles across all triangles was served as mean surface curvature and quantified overall surface roughness, with larger values indicating greater roughness. Together, these four variables allowed us to assess whether more extensively reduced spheroids display more standardized, symmetrical, and regular morphologies-characteristics expected in deliberate shaping strategies.

We conducted Spearman’s rank correlation analysis between two sets of variables, reduction intensity indicators and morphological attributes. This non-parametric method is appropriate for small sample sizes and data that do not follow a normal distribution. Spheroids and subspheroids from Qianshangying were included in the analysis.

# Results

## Morphometric analysis

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| Table 1: Summary of core typology and morphological parameters.   | ID | Rock\_type | Blank type | Final morphology | Typology | typology by SPHARM | Sphericity | SHE | Cortex covered | | --- | --- | --- | --- | --- | --- | --- | --- | --- | | QSY\_A\_0256 | Lava | Cobble | Polyhedral | Polyhedron | Ellipsoid or box | 0.866 | 1.020 | NA | | QSY\_A\_0562 | Other-quartz | Nodule | Cubical | Polyhedron | Discoid-like | 0.827 | 1.043 | NA | | QSY\_A\_0570 | Lava | Cobble | Cubical | Polyhedron | Discoid-like | 0.826 | 1.080 | NA | | QSY\_A\_0576 | Lava | Flake | Pyramidal | Multifacial | Discoid-like | 0.809 | 1.050 | NA | | QSY\_A\_0579 | Chert | Nodule | Pyramidal | Polyhedron | Discoid-like | 0.799 | 1.054 | NA | | QSY\_A\_0680 | Chert | Nodule | Pyramidal | Polyhedron | Discoid-like | 0.803 | 1.039 | NA | | QSY\_A\_0682 | Lava | Cobble | Polyhedral | Polyhedron | Sphere or rounded cube | 0.917 | 1.010 | NA | | QSY\_A\_0699 | Lava | NA | Cubical | Polyhedron | Discoid-like | 0.881 | 1.025 | NA | | QSY\_A\_0700 | Other-quartzite | Cobble | Pyramidal | Polyhedron | Sphere or rounded cube | 0.893 | 1.017 | Y | | QSY\_A\_0702 | Lava | Cobble | Pyramidal | Multifacial | Discoid-like | 0.842 | 1.042 | Y | | QSY\_A\_0735 | Lava | Cobble | Pyramidal | Polyhedron | Sphere or rounded cube | 0.868 | 1.020 | NA | | QSY\_A\_0938 | Lava | NA | Pyramidal | Polyhedron | Discoid-like | 0.869 | 1.027 | NA | | QSY\_A\_1098 | Lava | NA | Rounded | Spheroid | Ellipsoid or box | 0.919 | 1.013 | NA | | QSY\_A\_1111 | Chert | Nodule | Pyramidal | Polyhedron | Ellipsoid or box | 0.872 | 1.023 | NA | | QSY\_A\_1246 | Lava | Nodule | Polyhedral | Subspheroid | Sphere or rounded cube | 0.893 | 1.011 | NA | | QSY\_A\_1304 | Lava | Cobble | Pyramidal | Multifacial | Sphere or rounded cube | 0.927 | 1.013 | Y | | QSY\_A\_1307 | Dolomite | Nodule | Cubical | Polyhedron | Discoid-like | 0.868 | 1.037 | NA | | QSY\_A\_1333 | Lava | NA | Cubical | Polyhedron | Discoid-like | 0.861 | 1.031 | NA | | QSY\_A\_1517 | Lava | Flake | Pyramidal | Multifacial | Discoid-like | 0.796 | 1.075 | NA | | QSY\_A\_1584 | Lava | NA | Pyramidal | Polyhedron | Sphere or rounded cube | 0.855 | 1.019 | NA | | QSY\_A\_1777 | Dolomite | Cobble | Rounded | Spheroid | Sphere or rounded cube | 0.897 | 1.011 | NA | | QSY\_A\_1941 | Lava | Cobble | Polyhedral | Subspheroid | Sphere or rounded cube | 0.901 | 1.011 | Y | | QSY\_A\_2048 | Lava | Cobble | Cubical | Subspheroid | Discoid-like | 0.891 | 1.030 | NA | | QSY\_A\_2049 | Lava | Cobble | Pyramidal | Multifacial | Discoid-like | 0.869 | 1.031 | Y | | QSY\_A\_2213 | Lava | NA | Polyhedral | Subspheroid | Sphere or rounded cube | 0.878 | 1.011 | NA | | QSY\_A\_2381 | Lava | Cobble | Pyramidal | Multifacial | Ellipsoid or box | 0.876 | 1.028 | Y | | QSY\_A\_2599 | Lava | Cobble | Polyhedral | Polyhedron | Ellipsoid or box | 0.902 | 1.017 | Y | | QSY\_A\_2600 | Dolomite | Cobble | Rounded | Spheroid | Sphere or rounded cube | 0.927 | 1.010 | NA | | QSY\_A\_2611 | Dolomite | Nodule | Polyhedral | Multifacial | Discoid-like | 0.820 | 1.040 | Y | | QSY\_A\_2717 | Lava | Cobble | Polyhedral | Subspheroid | Sphere or rounded cube | 0.905 | 1.011 | NA | | QSY\_A\_2723 | Lava | Cobble | Rounded | Spheroid | Sphere or rounded cube | 0.907 | 1.009 | NA | | QSY\_A\_2797 | Lava | NA | Rounded | Spheroid | Sphere or rounded cube | 0.938 | 1.004 | NA | | QSY\_B\_003 | Lava | Cobble | Rounded | Spheroid | Sphere or rounded cube | 0.915 | 1.015 | NA | | QSY\_B\_072 | Lava | Cobble | Polyhedral | Subspheroid | Ellipsoid or box | 0.902 | 1.020 | Y | | QSY\_B\_136 | Lava | Cobble | Polyhedral | Polyhedron | Ellipsoid or box | 0.879 | 1.019 | NA | | QSY\_B\_140 | Dolomite | Nodule | Polyhedral | Polyhedron | Discoid-like | 0.886 | 1.024 | Y | | QSY\_B\_159 | Lava | Cobble | Pyramidal | Multifacial | Discoid-like | 0.863 | 1.024 | Y | | QSY\_B\_168 | Lava | Cobble | Cubical | Polyhedron | Ellipsoid or box | 0.899 | 1.024 | NA | | QSY\_B\_186 | Dolomite | Nodule | Polyhedral | Polyhedron | Discoid-like | 0.869 | 1.027 | NA | | QSY\_B\_189 | Lava | Cobble | Cubical | Subspheroid | Ellipsoid or box | 0.905 | 1.016 | NA | | QSY\_B\_320 | Lava | Cobble | Cubical | Polyhedron | Discoid-like | 0.859 | 1.053 | NA | | QSY\_B\_435 | Dolomite | Nodule | Cubical | Polyhedron | Ellipsoid or box | 0.858 | 1.020 | Y | |

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| Figure 4: A. Mean spherical harmonic power spectrum. B. Variance distribution by spherical harmonic degree. C. Distribution of SHE and sphericity by artefact type. D. Correlation of sphericity and spherical harmonic energy |

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| Figure 5: A. UMAP plot showing distinct clusters of shapes derived from SPHARM. B. UMAP plot of SPHARM-derived shape features colored by types. UMAP plot axes represent relative positions in a reduced-dimension morphospace and do not have a direct physical interpretation. |

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| Figure 6: Shape reconstruction of archaeological spheroids using SPHARM (various lmax levels) |

[Table 1](#tbl-1) summarizes the basic information (rock type, blank type, final morphology, and cortex coverage) and morphological analysis results (classifications derived from SPHARM, values for sphericity and spherical harmonic energy) of the spheroids, subspheroids, polyhedrons and multifical cores involved in the research. From this table, we can observe distinctions between spheroids and subspheroids (n = rn\_sub\_spheroid`) on the one hand, and polyhedrons and multifacial cores (n =29) on the other. In the subsequent analysis, these categories are treated as two separate groups for comparison.

Our sphericity results reveals a clear difference between the group of spheroids and the group of polyhedrons and multifacial cores. The mean sphericity of spheroids (0.906) is notably higher than that of polyhedrons and multifacial cores (0.861), with a Wilcoxon rank-sum test yielding W = 37, p = . This result indicates that spheroids possess a more spherical geometry overall, supporting their typological classification as a distinct type.

We conducted shape analysis using spherical harmonic decomposition, setting the maximum degree to 20 (lmax=20, [Figure 6](#fig-SPHARM-Reconstruction-by-Degree)). This choice ensures that sufficient geometric detail is captured while avoiding high-frequency noise and overfitting artifacts. After normalization, all models have their degree 0 (l=0) coefficient set to 1, allowing for meaningful comparison across different models.

Subsequently, we computed the rotation-invariant power spectrum. Here we present the power spectrum of different groups, including the group of spheroids, group of polyhedrons and multifacial cores, and the total of all these categories combined ([Figure 4](#fig-sp-summary)). The results show that the spheroid group has significantly lower power than polyhedrons and multifacial cores at both low and high degrees, indicating that spheroids and subspheroids possess a more symmetrical overall shape and more regular local features. In addition, the spheroid group exhibits smaller inter-group morphological variation than polyhedrons and multifacial cores, particularly at low degrees. Then we performed a Variance Analysis on the power of each harmonic degree. The results indicate that l=2 and l=3 exhibit the highest variance across the sample, suggesting that these low-degrees capture the most significant shape variation. Specifically, l=2 reflects elongation or flattening, while l=3 reflects a sphere with octupole (pear-shaped) deformation exhibits a triaxial asymmetry that departs from both spherical and ellipsoidal symmetry.

To reduce the dimensionality and visualize the structure of shape variation, we applied a Uniform Manifold Approximation and Projection (UMAP) to the normalized power spectrum. The UMAP reveals distinct clusters in the first two dimensions of the shape space. These clusters correspond to reference models of sphere, rounded cube, ellipsoid, rounded box and disc-like ([Figure 5](#fig-UMAP-combined)). This demonstrates that these stone artifacts occupy distinguishable regions in the shape space, with proximity to the sphere or elongation or flattening along specific axes emerging as key differentiating features. Most artifacts typologically classified as spheroids or subspheroids were grouped into the “sphere” and “rounded cube”, and few into “ellipsoid” and “box” clusters, indicating their consistent, near-spherical shapes ([Figure 5](#fig-UMAP-combined)).

However, a few Multifacial cores and Polyhedrons also appeared in the near-spherical region. This can be attributed to their high cortex coverage or limited flake removals, which likely preserved their originally rounded shapes and led to their grouping alongside spheroids. Some artifacts are identified as spheroids or subspheroids but grouped as ellipsoid or rounded box, because they exhibit a long axis. However, both in the assessment of hominins and in our evaluation, these shapes are considered close to spherical, especially when they display large edge angles and rounded surface.

The UMAP-based groupings also correspond to significant differences in sphericity, as indicated by a Kruskal–Wallis test ( = 19.93, df = 2, p = ). The result shows statistically significant differences in sphericity among the shape clusters, further supporting the effectiveness of the spherical harmonic approach in capturing meaningful morphological variation.

The spherical harmonic energy (SHE), a novel metric introduced here, quantifies the geometric approximation of a shape to an ideal sphere. Normalized SHE approaching unity indicates progressively spherical configurations, while deviations from unity reflect morphological irregularity. Our analysis demonstrates significant negative correlation between SHE and classic sphericity measures (r = -0.83, df = 40, p = )), validating its efficacy as a proxy for how closely an object approximates a spherical form ([Figure 4](#fig-sp-summary)).

Statistical comparisons reveal distinct SHE distributions between groups: the group of spheroids exhibit a mean SHE of 1.013, whereas multifacial cores and polyhedron demonstrate significantly higher irregularity (mean SHE = 1.032). The Wilcoxon rank-sum test confirms robust inter-group divergence (W = 340, p = ), confirming the distinguishability of spheroid group from Qianshangying.

The pursuit of a standardized and distinct spherical form among spheroids is further supported by our findings. Using the Coefficient of Variation (CV), defined as the sample standard deviation divided by the sample mean, we assessed the consistency of sphericity within the spheroid and subspheroids. Eerkens and Bettinger (2001) suggested that a CV of under 1.7% (0.017) is a realistic threshold for manually-produced archaeological artifacts. Both sphericity and SHE values yielded low CVs (0.017 and 0.006, respectively), indicating that group of spheroids maintain a highly standardized rounded shape. In contrast, the group of multifacial cores and polyhedron has a higher CV of 0.039 and 0.017 respectively.

## Technological analysis

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| Figure 7: Ternary plot showing flake scar orientation analysis |

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| Figure 8: Diacritical analysis of Qianshangying spheroids |

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| Figure 9: Hypothetical spheroid shaping process at Qianshangying |

Diacritical analysis of spheroid and subspheroid surfaces reveals a structured and recurrent reduction sequence comprising three phases ([Figure 8](#fig-spheroids-2797-1098)). Phase one was a unidirectional or bidirectional total exploitation, belonging to one kind of volume exploitation. Large and flat surfaces of the cobble were selected as platforms for striking toward the opposite surface. Knapping proceeded until the peripheral volume was fully exploited, resulting in an approximately cubic form. Phase two was peripheral centripetal exploitation. In this phase, previous removals in phase one serve as platforms for centripetal flaking around the core periphery. This represents a surface exploitation stage. A notable feature is the angle between the face’s ventral surface and platform (i.e. core edge angle), which often exceeds 90°. This phase contributes significantly to the increasingly spherical shape of the artifact. Phase three was the production of small scars on ridges or intersections of previous flake scars, resulting in a rounding and smoother surface, further enhancing roundness.

Among the spheroids and subspheroids in Qianshangying site, 7 pieces fall within Phase three of the reduction sequence, 1 piece in phase two, and 4 pieces in phase one (see supplymentary material-QSY\_A.xlsx and QSY\_B.xlsx). However, one subspheroid bypassed Phase 1 and instead employed a strategy of bifacial centripetal exploitation combined with edge refinement. Notably, in this case the angle between the two flaking surfaces approaches 90°, distinguishing this subspheroid from typical core of discoid. This indicates that the purpose of reduction was not the production of flakes, but rather the direct shaping of the artifact into its final spherical form. Also, it is important to note that due to the high degree of reduction intensity observed in some spheroids, phases prior to the visible sequence were often obliterated. We hypothesize the existence of a Phase zero, potentially involving roughing-out of the cobble or an earlier cycle of Phases one to three [Figure 9](#fig-shaping-process).

Scar orientation analysis further supports the interpretation of a systematic reduction sequence in the production of Qianshangying spheroids and subspheroids. [Figure 7](#fig-benn-ternary-plot) shows that spheroids tend to cluster together, with elongation ratios ranging from 0.118 to 0.646 and isotropy ratios from 0.182 to 0.634. These elongation ratios suggest that the spheroids underwent unidirectional or bidirectional total exploitation, typical of Phase one, resulting in relatively high elongation values. Then the peripheral centripetal exploitation, namely Phase two, appears to have contributed to a certain degree of isotropy in scar orientation, and higher isotropy ratios are associated with more spherical forms. Subspheroids exhibit greater variability in both elongation and isotropy ratios, reflecting less standardized reduction than spheroids.

Multifacial cores and polyhedrons display a wide and dispersed distribution in the ternary plot, without forming any distinctive cluster. Their scar patterns show considerable variability in both elongation and isotropy, reinforcing the interpretation that these cores lack removal organization. Multifacial cores typically exploit natural angles with core rotation occurring without a predetermined plan, which belongs to an opportunistic flaking strategy, while polyhedrons, despite showing a higher degree of reduction, follow a similarly unstructured sequence. This distinction highlights the fundamental technological difference between group of polyhedrons and multifacial cores and group of spheroids at Qianshangying. While they used to be considered as a continuous reduction process, our results show that in fact polyhedrons and multifacial cores represent exhausted cores, whereas spheroid group reflects the presence of a distinct conceptual template and systematic reduction plan.

## Shaping strategy efficiency

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| Table 2: Summary of spheroid shaping intensity and shape features. SDI = scar density index, SHE = spherical harmonic energy   | ID | Scar number | Removal ratio | SDI | Mean edge angle | Curvature | Sphericity | SHE | | --- | --- | --- | --- | --- | --- | --- | --- | | QSY\_A\_1098 | 29 | 0.973 | 0.003 | 128.338 | 7.998 | 0.919 | 1.013 | | QSY\_A\_1246 | 31 | 0.921 | 0.003 | 123.936 | 8.090 | 0.893 | 1.011 | | QSY\_A\_1777 | 14 | 0.927 | 0.005 | 122.208 | 7.979 | 0.897 | 1.011 | | QSY\_A\_1941 | 8 | 0.681 | 0.001 | 109.423 | 9.902 | 0.901 | 1.011 | | QSY\_A\_2048 | 22 | 0.851 | 0.000 | 118.574 | 8.133 | 0.891 | 1.030 | | QSY\_A\_2213 | 26 | 0.922 | 0.002 | 114.985 | 8.873 | 0.878 | 1.011 | | QSY\_A\_2600 | 22 | 0.852 | 0.001 | 124.385 | 7.145 | 0.927 | 1.010 | | QSY\_A\_2717 | 20 | 0.860 | 0.001 | 122.426 | 8.954 | 0.905 | 1.011 | | QSY\_A\_2723 | 27 | 0.918 | 0.001 | 134.926 | 8.275 | 0.907 | 1.009 | | QSY\_A\_2797 | 28 | 0.960 | 0.002 | 135.403 | 7.453 | 0.938 | 1.004 | | QSY\_B\_003 | 14 | 0.647 | 0.000 | 120.931 | 6.750 | 0.915 | 1.015 | | QSY\_B\_072 | 4 | 0.623 | 0.000 | 115.484 | 8.008 | 0.902 | 1.020 | | QSY\_B\_189 | 15 | 0.782 | 0.001 | 117.941 | 7.626 | 0.905 | 1.016 | |

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| Figure 10: Spearman correlation matrix of shape variables. Red star indicates p < 0.05 |

For all spheroids and subspheroids, we conducted shaping efficiency analysis. [Figure 10](#fig-spearman-correlation-matrix) shows significant positive correlations among the three variables representing reduction intensity: scar number, removal ratio, and SDI. Among them, scar counts show significant positive correlations with both removal ratio (ρ = 0.74, p = ) and SDI (ρ = 0.64, p = ). Removal ratio and SDI exhibit a stronger and more highly significant correlation (ρ = 0.89, p = ). These two variables incorporate surface area in their calculation, making them more effective in capturing the density and intensity of reduction, and therefore more reliable indicators of the shaping process in spheroids.

Among the shape descriptors, we observed several significant correlations. Mean edge angle was positively correlated with sphericity (ρ = 0.68, p = ) and negatively correlated with Spherical Harmonics Power (SHE) (ρ = -0.59, p = ), indicating that greater edge angles are associated with more spherical and regular forms. As noted in previous studies, mean edge angle is a key variable in capturing the morphology of spheroids (Titton et al., 2020). This correlation between edge angle and SHE may help explain why spheroids were often interpreted as exhausted cores in earlier research (Sahnouni et al., 1997). Indeed, spheroids must be significantly reduced, as achieving a near-perfect spherical shape typically results in increased edge angles, making further flake removal difficult. However, the reverse is not necessarily true, as not all exhausted cores are shaped like spheroids.

Curvature was only significantly correlated with sphericity (ρ = -0.57, p = ), suggesting that smoother surfaces tend to approximate spheres more closely. Its lack of correlation with other variables may reflect its focus on local surface texture, while edge angle and SHE capture broader aspects of shape regularity and symmetry. The weak correlation between sphericity and SHE may result from the small sample size or their different sensitivities: sphericity, based on area and volume, tolerates surface variation, while SHE responds more to asymmetry and shape irregularity. Thus, even in specimens with similar sphericity, surface differences can produce substantial variation in SHE. The analysis of spheroid shape variables indicates that mean edge angle, curvature, sphericity, and SHE each capture distinct aspects of spheroid morphology, which explains the varying strengths of correlation observed among them.

Significant correlations were found between reduction intensity and mean edge angle and SHE. Mean edge angle was positively correlated with both scar number (ρ = 0.68, p = ) and removal ratio (ρ = 0.61, p = ), while SHE was negatively correlated with removal ratio (ρ = -0.60, ) and SDI (ρ = -0.58, p = ). These results suggest that as reduction progresses, spheroids develop larger edge angles and lower SHE, indicating increased regular forms and global symmetry.

However, no significant correlations were observed between reduction variables and sphericity or curvature. This implies that increased reduction does not necessarily produce smoother surfaces. Such patterns likely reflect the technological nature of the samples: the analyzed spheroids and subspheroids are “faceted” products of flake removal. Flaking increases surface complexity by adding edges and angular intersections, which may elevate curvature while also expanding surface area, factors that can distort sphericity values. For instance, a smooth, naturally rounded cobble might exhibit lower curvature and a sphericity closer to 1 than a heavily flaked spheroid. Therefore, the signficnt correlation between reduction intensity and SHE and mean edge angle, but not sphericity or curvature, suggests that shaping efforts prioritized achieving symmetrical and regular, coherent forms rather than naturally polished and smooth surfaces.

Overall, the observed relationships between reduction intensity and shape descriptors, particularly mean edge angle and SHE, support the interpretation that spheroid shaping was an efficient and purposeful process. The goal was to produce well-structured, globally spherical spheroids rather than smooth objects.

# Discussion

## Do the Qianshangying spheroids represent a shaping strategy?

According to the results of our morphological and technological analysis, we can summarize the technical strategy employed in the production of faceted spheroids from Qianshangying. This strategy consists of a series of sequential phases ([Figure 9](#fig-shaping-process)): a potential rough-out phase, volume exploitation aimed at forming a symmetrical cubic shape, surface exploitation to approximate a spherical geometry, edge refinement, and potentially the repetition of earlier phases. The existence of a repetitive phase is supported by the observation that while the original cobble blanks from Qianshangying display considerable size variation, the finished spheroids and subspheroids, although few of them are relatively large or small, mostly cluster around a diameter of 6–9 cm [Figure 2](#fig-basic-characteristics). This suggests that the production of spheroids may have involved multiple cycles of reduction, and further implies that a diameter of 6–9 cm was considered an optimal or intended size in the knapping process.

Therefore, it can be inferred that the Qianshangying hominins deliberately employed a standardized production approach to create spheroids with consistent and formalized shapes. The technological strategy reflected in the Qianshangying faceted spheroids includes the use of a conceptual template, standardized production, and the achievement of a target product, which together demonstrate that this was a shaping strategy. This stands in contrast to flaking strategies, where the primary objective is the removal of usable flakes rather than the shaping of a cobble into a predetermined morphology (Duke et al., 2021; Inizan et al., 1999).

The evolutionary origins of shaping strategies are most commonly linked to the Acheulean, particularly those exemplified by bifacial shaping strategies on handaxes (Glynn L. Isaac, 1986). These strategies gradually became more refined, with mature bifacial shaping marked by the concept of bifacial symmetry, thinning and edge refinement, and the achievement of a standardized final shape (Beyene et al., 2013; Shipton et al., 2019). Compared to flaking technology in Oldowan, these processes demand greater cognitive planning and precise manual control (Stout et al., 2015; Wynn, 1995). Although the spheroid group from Qianshangying do not qualify as Large Cutting Tools (LCTs), nor does the site yield other typically Acheulean products, the faceted spheroids nonetheless exhibit a level of technological and morphological complexity comparable to that of LCTs. They also share key features, including a hierarchical and standardized reduction sequence and a high degree of symmetry and regularity in the final product.

These findings also contribute to the long-standing debate over the nature of spheroids-whether they should be interpreted as byproducts of flake production, or as targeted end products of shaping strategies. In the case of the Qianshangying faceted spheroids, the evidence strongly supports the latter. Faceted spheroids recovered from other Early Pleistocene sites in Barranco Leon and ’Ubeidiya have also been reported to show evidence consistent with shaping strategy (Muller et al., 2023; Titton et al., 2020). These intentionally shaped spheroids appear contemporaneous with, or even predate, the emergence of Acheulean technology. It is important to note, however, that many spheroids from East Africa may not fall into this category. As noted by Mora and De La Torre (2005), these quartz spheroids may have been produced through percussive techniques. They are often covered with battering marks, exhibit smoother surfaces and lack ridges, features that suggest they may be better classified as bolas within a typological framework (Leakey, 1971). It may be more appropriate to describe these artifacts in technological terms, rather than relying on morphology-based typologies that can lead to confusion. For instance, referring to them as battering spheroids could help distinguish them from faceted spheroids.

Another issue we aimed to address is the relationship between polyhedrons, spheroids, and bolas. While no bolas were identified at Qianshangying, our quantitative analyses clearly differentiated polyhedrons from spheroids or subspheroids. These two artifact types differ in size, morphology, and production sequence. Polyhedrons at Qianshangying represent heavily reduced cores, whose edge angle increase results from extensive flake removal. Their primary purpose lies in producing flakes, placing them within a flaking strategy. In contrast, spheroids and subspheroids were intentionally shaped as end products, reflecting a shaping strategy. These two technological approaches of flaking and shaping strategies coexisted at Qianshangying, indicating a diversity of reduction goals.

However, we found that although the morphology and reduction technology of spheroid group and polyhedrons can be clearly distinguished, spheroids in early phases may be difficult to differentiate from cores. In their initial phases of reduction, spheroids often resemble cores due to similar flake removal patterns. At this stage, they may be classified as cores, especially since the flakes produced during the initial shaping are themselves usable. As Cabanès et al. (2022) mentioned, they could share a common operative chain before completing the final product. However, it remains unclear whether this typological transformation was intentional or unplanned.

## QSY spheroids in the context of East Asia

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| Figure 11: Map of Paleolithic Sites with Spheroids in China and Their Associated Lithic Industries. 1. Mujiaqiao, (Wei et al., 1984); 2. Liaohe river region, (Li and Xu, 1991); 3. Deshan Second Brick factory, (Xi, 1994); 4. Zhangjiatan, (Lixian County Museum, 1992); 5. Huzhua Mount., (Tan, 1999); 6. Fangniu Mount., (Fang et al., 2002); 7. Fanba, (Xia et al., 2022); 8. Xiaokongshan, (Xiaokongshan Joint Excavation Team, 1988); 9. Hejialiang, (Wang et al., 2014); 10. Longgangsi, (Lu et al., 2006); 11. Shangdan basin, (Wang et al., 2013); 12. Yaoshi basin, (Wang and Hu, 2000); 13. Choushuihe, (Dai and Xu, 1973); 14. Kehe, (Jia, 1962); 15. Shuigou, (Huang, 1964); 16. Hezhigou, (Liu et al., 1984); 17. Xigou, (Jia, 1959); 18. Dingcun, (Shanxi Provincial Institute of Archaeology, 2014; Tao et al., 1984); 19. Liujiacha, (Xie, 1982); 20. Dangcheng, (Wu and Sun, 1989); 21. Zhoukoudian Loc.1, (Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, 1985);22. Qianshangying, (Z. Ye et al., 2025); 23. Xujiayao, (Jia et al., 1979; Jia and Wei, 1976; Ma et al., 2011; Wang, 2016)); 24. Jinsitai, (Wang et al., 2010) |

In East Asia, spheroids constitute a technological category with broad temporal and spatial distribution (Yi et al., 2012), as shown in [Figure 11](#fig-Spheroids-distribution-China) (see the supplementary materials for a table of more information about these sites). In addition to the one spheroid collected near the Gongwangling site in Shanxi (Dai and Xu, 1973), the earliest dated spheroids originate from Zhoukoudian Locality 1 (ZKD Loc.1) (Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, 1985), attributed to the early Middle Pleistocene, and not far from Qianshangying. In terms of geographic range, the southernmost and westernmost occurrences of spheroids are found at the Mujiaqiao site (MJQ) in Yunnan (Wei et al., 1984), while the northernmost spheroids come from the Jinsitai site (JST) in Inner Mongolia (Wang et al., 2010). The widespread occurrence of spheroids across time and space in East Asia may indicate their role as a generalized or multipurpose tool within Pleistocene contexts, capable of serving diverse functions in varying ecological and cultural settings.

Over 1522 spheroids have been identified across more than 23 archaeological sites or localities in East Asia However, many of these findings derive from surface surveys rather than systematic excavations, and the recovered quantities are often limited. Thus, the number of spheroids per site varies considerably: 19 sites have yielded fewer than ten specimens each. Qianshangying is typical with ‘r n\_spheroids’ spheroids. By contrast, three sites-Xujiayao (XJY), Dingcun (DC), and JST—have produced substantial assemblages, each exceeding 100 spheroids (Shanxi Provincial Institute of Archaeology, 2014; Wang, 2016; Wang et al., 2010). Notably, XJY alone has yielded over 1,000 specimens (Wang, 2016).

The raw materials used for spheroids at these archaeological sites primarily include quartz, quartzite, sandstone, and limestone, with occasional occurrences of lava and dolomite at a few localities, such as Qianshangying. Among these, quartz and quartzite are the most widely used materials, found at 18 sites across China. In contrast, spheroids made of sandstone and limestone are mainly concentrated at sites distributed along the Fen River and Li River basins in Central China. Previous researches have observed that the morphological characteristics of spheroids are influenced by the physical properties of the raw materials (Tao et al., 1984). For example, at the DC site, spheroids made from quartz tend to be irregular and angular, possibly due to the fragile nature of quartz. In comparison, those made from softer materials such as limestone and sandstone are generally more rounded and smoother, with flake scars that appear more diffuse or less distinct (Tao et al., 1984).

Three primary techniques have been identified in the manufacture of spheroids in China: flaking, involving the removal of flakes to shape the object (e.g., Qianshangying, MJQ, (Wei et al., 1984)); pecking, where two blanks are struck together to round off edges, sometimes by splitting a cobble and using the halves against each other (e.g., DC, (Shanxi Provincial Institute of Archaeology, 2014)); and battering, involving repeated percussion of a polyhedrons (e.g., ZKD Loc.1, (Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, 1985)). Experimental studies suggest that pecking and battering yield similar efficiency and spherical form (Lu et al., 2021). Many sites, such as XJY and DC, show evidence of multiple techniques, including combined or sequential methods like pecking after flaking to improve roundness (Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, 1985; Tao et al., 1984). No clear relationship has yet been established between raw material types and specific production methods.

We found six sites exhibiting similar strategies to QSY. For example, at DC and MJQ, thick and flat cobbles were selected and shaped through peripheral flaking, producing roughly approximately cubic shape (Tao et al., 1984; Wei et al., 1984). MJQ specimens retain parts of the cortex, while at DC, flakes with large exterior and small interior platform angles were removed from blanks to increase edge angles and enhance roundness (Tao et al., 1984; Wei et al., 1984). Among the six sites, all but MJQ are located within the Fen River and Lishui River regions. These sites were grouped into the Keheng–Dingcun techno-complexes and Lishui techno-complexes, characterized by trihedral picks (Fang et al., 2002; Jia, 1962; Lixian County Museum, 1992; Shanxi Provincial Institute of Archaeology, 2014; Tan, 1999). The trihedral picks were produced by striking the dorsal surfaces of large flakes to concentrate edges at the tip, resulting in triangular outlines and robust pointed ends, classifying them as large cutting tools (LCTs)(Kuman et al., 2014; Li et al., 2018; Yang et al., 2016). This is a significant observation, as it implies that spheroid production techniques similar to those at Qianshangying are more frequently associated with lithic assemblages characterized by intentional shaping strategies.

It should be emphasized, however, that we do not intend to imply a direct association between faceted spheroids and Acheulean technology. We infer that faceted spheroids in China appear to represent a shaping tradition that shares the same crucial technological competencies as LCTs (Cabanès et al., 2024; Glynn L. Isaac, 1986; Leakey, 1971), and this explains why they often occur in Acheulean techno-complex. We now find that faceted spheroids occur at QSY within the small flake tool industry of northern China. Since this industry was previously regarded as a simple core and flake technology, the presence of faceted spheroids suggests that it is more complex and exhibits greater variability than previously thought.

Similarly, we may need to reconsider the technological complexity implied by faceted spheroids, even when they occur in early cultural contexts traditionally regarded as simple. Faceted spheroids appear in what is considered the Late Oldowan, if a chronological boundary is set at 2.0 Ma to distinguish between Early and Late Oldowan (Gallotti et al., 2018). The growing recognition of technological diversity within the Oldowan has led to a broader consensus that the Late Oldowan includes signs of innovation, such as more complex flaking patterns and decreased morphological variability in flakes (Braun et al., 2019; Gallotti et al., 2018). Faceted spheroids, we propose here, may represent one of the key indicators of this increasing technological complexity during the Late Oldowan (Titton et al., 2020).

In particular, if future research can demonstrate that these faceted spheroids also represent a deliberate shaping strategy, this may indicate a level of technical skill approaching that of the earliest Acheulean, or perhaps even foreshadowing its emergence. After all, faceted spheroids already embody one of the key innovation characteristics of the Acheulean, that is, the imposition of a specific mental template onto blanks in order to produce tools with broadly similar overall forms (De la Torre, 2016; Glynn L. Isaac, 1986).

# Conclusion

Quantitative approaches to studying spheroids remain limited (De Weyer, 2017; Muller et al., 2023; Titton et al., 2020). We propose a complete, efficient, reproducible and transparent methodological framework here based on spherical harmonics to quantitatively assess morphological variation among flaked pieces, allowing for the distinction between cores and spheroids and evaluating the degree of morphological standardization in spheroids. Past approaches to analyzing the morphology of flaked pieces have been limited, with geometric morphometrics being the last major method innovation (Cao et al., 2025; Hallinan and Cascalheira, 2025; Lycett and Von Cramon-Taubadel, 2013). However, this method has significant constraints, including the requirement for homologous landmarks, which limits its applicability to artifacts like cores of various shapes and spheroids. Spherical harmonics offer a viable alternative, showing strong potential for precision and interpretability. We can reasonably expect broader applications of this method across a range of archaeological artifacts in the future.

In principle, any closed three-dimensional object can be analyzed using spherical harmonics. In archaeology, materials such as spheroids or cores, ceramic vessels, plant seeds, and animal crania are particularly well suited to this approach, as their overall forms approximate spheres or ellipsoids, making them readily mappable onto the unit sphere for spherical harmonic expansion. Low-order expansions efficiently capture their primary morphological features, while the combination of low-order and high-order coefficients allows for a distinction between overall shape (e.g., symmetry, inflation, elongation) and local details (e.g., decorations, ridges, protrusions). Moreover, these objects generally do not emphasize orientation, enabling the use of rotationally invariant spherical harmonic power spectra to quantify shape variation. For objects with weaker symmetry or greater surface complexity, however, higher-order expansions are required, increasing computational cost and complicating the interpretation of coefficients. As a tool for morphological research, spherical harmonics are particularly effective in addressing issues of shape symmetry and standardization (Grieb et al., 2022; Muller et al., 2023). Moreover, owing to the high precision of spherical harmonic decomposition, they offer significant advantages in investigating morphological variation and evolution both within and between groups (Link et al., 2024; Medyukhina et al., 2020; Noshita et al., 2025).

By applying a range of quantitative methods, we conducted an integrated morphological and technological study of the Qianshangying spheroids. Our results demonstrate that these spheroids were produced through a programmed reduction strategy aimed at achieving standardized spherical forms, primarily using hard-hammer direct percussion. The evidence of shaping strategies on Qianshangying spheroids confirms that they were intentionally made tools with conceptual template, rather than exhausted cores. This distinguishes them from polyhedrons or multifacial cores in their terminal reduction stages. Traditionally, lithic technology in northern China prior to the Late Pleistocene has been considered stagnant and generally classified as simple core and flake industry. However, the Qianshangying assemblage from ~429ka clearly reveals a higher level of technological complexity.

This paper also presents one of the first systematic overviews of the spatial and temporal distribution and technological variability of spheroids within China. We found that Chinese spheroids display considerable diversity in raw materials, production techniques, and morphology. Some assemblages contain spheroids that may be comparable to those from Qianshangying and tend to appear within Acheulean or shaping-oriented techno-complexes, often dated later than Qianshangying. This highlights the particular significance of the Qianshangying spheroids. However, the current dataset remains limited, and many sites lack detailed morphological and technological studies of spheroids, hampering broader inferences about hominin technological behaviors. We therefore emphasize the need for site-specific analysis of spheroids in future research.

Given the limitations of traditional typology in capturing the functional, morphological, and technological variability of spheroids across sites, we argue that multiple method approaches are essential. From the perspective of typology, spheroids have often been dismissed as poor marker of hominin behavior due to their wide spatial and temporal distribution. However, more recent studies increasingly reveal their diversity and potential as markers of hominin technological behavior (Titton et al., 2020; Vaquero and Romagnoli, 2018). For example, distinctions between flaking-based and battering-based spheroids, along with patterns of raw material selection, production goals, and associations with specific subsistence strategies or environmental adaptations, may prove meaningful (Cabanès et al., 2024). Beyond the methods of morphological and technological analysis used here, future studies incorporating functional analysis and experimental replication will further enhance our understanding.

# CRediT authorship contribution statement

Ye Zhi: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Ben Marwick: Writing – original draft, review & editing, Supervision, Project administration, Methodology, Conceptualization. Li Hao: Writing – review & editing, Conceptualization, Funding acquisition. Shuwen Pei: Writing – review & editing, Conceptualization, Funding acquisition.

# Data availability statement

The 3d models from QSY site used in this study are openly available at https://osf.io/ctne9/?view\_only=eb93ea8a29bb4b40a407f7eba39c6fc1

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# Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Colophon

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