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Lithic miniaturization in South China since the terminal Pleistocene:

A multivariate analysis of lithic reduction from Fodongdi, Fulin and Xiqiaoshan

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Abstract: Lithic miniaturization is a key adaptive and technological feature of human populations and one of the key cultural hallmarks in the Late Pleistocene of Eastern Asia. In northern China this form of stone tool technology is well represented, including by microblade technology. Lithic miniaturization has been identified in South China, though this technological feature has received little research attention in comparison to the north. Here, we examine three miniaturized lithic assemblages in South China, ranging from the terminal Pleistocene to middle Holocene. To examine technological variations in lithic miniaturization, the three assemblages were subject to comparative quantitative analyses, including principal component analysis (PCA), K-means clustering and the Zingg system. The three sites were found to exhibit varied temporal and geographic patterns of lithic miniaturization across South China, potentially related to fluctuating climatic conditions and changes in population dynamics since the Late Pleistocene.

Keywords: lithic technology; human evolution; bipolar piece; microblades

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1 Introduction

During the Late Pleistocene our species dispersed into a wide variety of environments across Asia, illustrating a range of behavioral adaptations to variable ecosystems (Bae *et al*., 2017; Roberts and Stewart, 2018; Zhang *et al*., 2018). The character of technological change differs greatly across this vast region both temporally and spatially (Bae, 2017; Yang *et al*., 2024a). Though great strides have been made in understanding technological patterns adopted by populations in Eastern Asia (Li *et al*., 2022; Wang *et al*., 2022; Yang *et al*., 2024b), technological changes through time remain poorly understood. South China is key for examining Late Pleistocene technological change as the region sits at the crossroads of human migration and cultural transmission, linking North China, the Qinghai-Tibet Plateau, and Southeast Asia (McColl *et al*., 2018; Wang *et al*., 2021; Zhang *et al*., 2022). South China is a region which appears to have had a diversity of adaptive behaviors across the Late Pleistocene and Holocene, in part owing to its varied terrain and diverse ecosystems (Xiao *et al*., 2014a, 2014b; Tian *et al*., 2019; Zhang *et al*., 2019).

Lithic miniaturization, which we define here as the systematic production and use of small-sized lithic artifacts, including backed tools, bladelets, and small retouched tools, is a phenomenon observed in many parts of the world during the Late Pleistocene (e.g. Elston and Kuhn, 2002; Petraglia *et al*., 2009; Villa *et al*., 2012; Pargeter and Shea, 2019; Wedage *et al*., 2019; Groman-Yaroslavski *et al*., 2020; Picin *et al*., 2022; Wang *et al*., 2022; Lin *et al*., 2023). It is associated with the development of modern behaviors (e.g. McBrearty and Brooks, 2000; Wang *et al*., 2022) and regarded as having adaptive advantages, including the efficient utilization of raw material, functional flexibility and transportability (Elston and Kuhn, 2002; Petraglia *et al*., 2009; Clarkson *et al*., 2018; Pargeter and Shea, 2019; Low and Pargeter, 2020).

Research in South China has been devoted to an understanding its cobble tool assemblages, as it forms a distinctive technological feature (e.g. Li and Zhang, 1984; Zhang, 1999; Ji *et al*., 2016; Li *et al*., 2019; Zhou *et al*., 2019; Xie *et al*., 2020; Wang, 2021; Li *et al*., 2022). More recently, however, investigators have highlighted the presence of miniaturized lithics in stone tool assemblages, including microblades, bladelet-like pieces, and small flake tools (e.g. IA-CASS *et al*., 2015, 2017; SPCRARI and HCACR, 2020; Zhu *et al*., 2020; SPCRARI and SH-CNU, 2021; Yang *et al*., 2022; Deng and Liu, 2023; Huan *et al*., 2023, 2024a; Zhao *et al*., 2023), inviting reconsideration of the potential technological diversity of this region during the Late Pleistocene. Given the limited evidence that has been reported to date and the lack of synthesis about lithic miniaturization, key questions remain unanswered. For example, we may ask how evident is lithic miniaturization in Late Pleistocene stone tool assemblages in South China? How do lithic technologies change through time, and do these correspond with changes in the environment and population of the region?

Here we examine three lithic assemblages from South China that contain miniaturized stone artifacts dating from the Late Pleistocene to the middle Holocene. We present detailed techno-typological analyses and inter-site comparisons to address temporal and spatial patterns, providing for an assessment of miniaturized toolkits and their reduction techniques. We discuss the implications of our findings for potentially understanding the long-term adaptive strategies of human populations in South China.

2 Materials and methods

2.1 Archaeological sites and lithic assemblages

Three archaeological sites were chosen for study, i.e., Fodongdi, Fulin, and Xiqiaoshan (Figure 1). The sites were chosen for study based on their reliable chronologies, varied geographic settings and quality of lithic assemblages. Based on stratigraphical context and dating, the sites range from the Late Pleistocene to the middle Holocene, providing a long-term diachronic picture of human occupation. The three sites are situated in different areas of South China, each with distinct environmental settings, including tropical forests, plateau margins, and coastal regions, providing an opportunity to examine and compare the strategy of lithic miniaturization in different ecological contexts (Figure 1). The three lithic assemblages have a diverse range of technologies and tool types, resulting in the analysis of more than 10,000 miniaturized lithic artifacts.

Fodongdi (23°44′14.38″N, 99°19′37.17″E, 593 m a.s.l.) is a Permian limestone cave site in the tropical forest of Mengjian village, Lincang city, Yunnan province, about 60 km from the China-Myanmar border (Figure 1). In 2017 and 2018, excavations were conducted by the Institute of Vertebrate Paleontology and Paleoanthropology (Chinese Academy of Science), together with the Yunnan Provincial Institute of Relics and Archaeology. Excavation of an area measuring 20 m^2 resulted in the recovery of lithic artifacts, fauna, and flora (Gao *et al.*, 2023; Huan *et al.*, 2024b). The stratigraphic profile shows three phases of deposit formation, phase A (18.4–17.0 ka BP), phase B (16.5–16.0 ka BP), and phase C (15.8–13.8 ka BP). More than 9000 lithics were identified, showing a high level of diversification, classifiable as products of Hoabinhian, core-flake, and bipolar flaking strategies (Huan *et al.*, 2024b). Discovered in the tropical-subtropical area where the small stone artifacts are uncommon, miniaturized bipolar lithics here provide a unique case.

Fulin (29°20′53.1″N, 102°40′58.0″E, 810 m a.s.l.) is an open-air site in the marginal area of Qinghai-Tibet Plateau, situated at the Hanyuan county, Ya’an city, Sichuan province (Figure 1). Discovered in the 1960s, the site has been excavated twice, first in 1972 and again in 2009–2010 (Zhang, 1977; SPCRARI and HCACR, 2020). More than 5000 lithics were recovered from an area measuring 300 m^2. The lithic assemblage features unique small-size flakes and bladelet-like pieces (Zhang, 1977; Huan *et al.*, 2023). OSL ages indicate that the deposit spans between 11.7–10.3 ka BP (SPCRARI and HCACR, 2020). A total of 1940 lithics excavated in 1972 were analyzed, showing that the assemblage is dominated by small sized lithics, including bladelet-like pieces (Huan *et al.*, 2022, 2023).

Xiqiaoshan Mountain (22°55′27″N, 112°59′17″E), an extinct volcano, is in the Pearl River Delta region, a coastal area in Guangdong province (Figure 1). More than 20 archaeological localities have been discovered across the Xiqiaoshan Mountain region since the 1950s. A large quantity of lithics, including microblade products were identified from those localities, providing a new understanding of the geographical distribution of microblade assemblages (The Kwangtung Provincial Museum, 1959; SGSYU, 1959; Jia, 1978; Huang *et al.*, 1979; Zeng, 1981; Zeng and Li, 1988; Zhang, 1993; Yang *et al.*, 2022; Zhu *et al.*, 2024). For this study, we observed 559 lithic artifacts from Localities 4 and 18. These sites were representative of microblade technology at Xiqiaoshan, providing an opportunity to examine 343 microblade cores (Zeng, 1981; Zeng and Li, 1988; Li, 2013; Yang *et al.*, 2022). Radio-

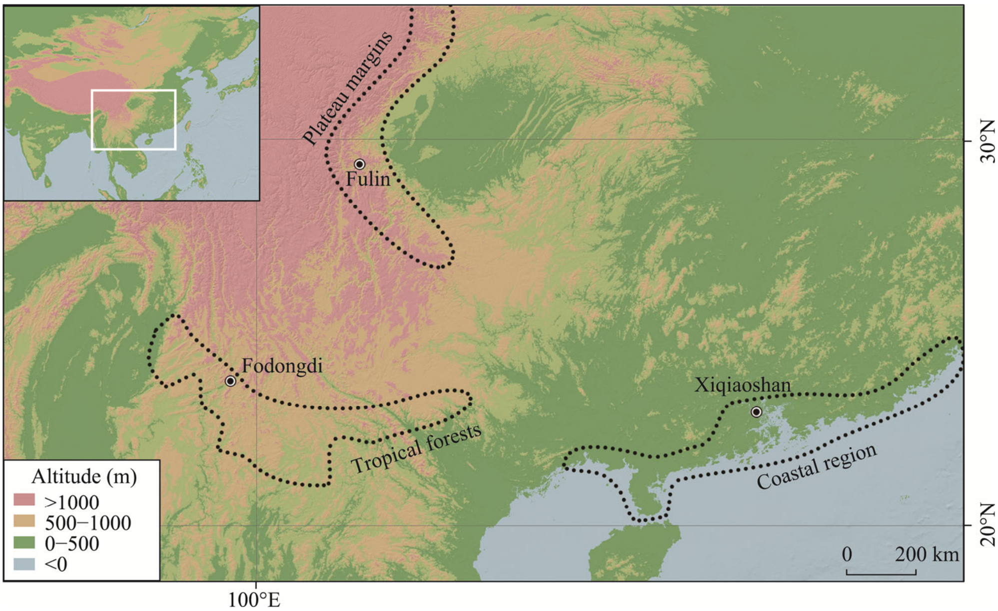

Figure 1 Geographical setting of the sites examined in this study. The dotted areas indicate the approximate range of the three different habitats. Colors denote different altitude zones.

carbon dates indicate that the microblade assemblages date to between 7.8–5.6 ka BP (Zeng and Li, 1988; Li, 2013; Yang *et al*., 2022).

2.2 Quantitative methods

A comprehensive techno-typological analysis of three lithic assemblages was conducted. In total, we observed and measured 12,226 lithic artifacts, selecting 1065 miniaturized lithics as key specimens for in-depth analysis and discussion in this paper. The measured and collected data of these 1065 miniaturized lithics included artifact size, weight, platform angle, platform size, platform numbers, reduction surface numbers, scar numbers, scar size, and other relevant attributes. To account for differences in assemblages and technological characteristics, we tailored the measurement parameters to ensure that all essential proxies were accurately recorded. To characterize their technological variability, we compiled quantifiable data based on a series of measurements, allowing for quantitative comparative analyses. Given the extensive number of attributes, meaningful comparison and visualization is sometimes difficult. To address this issue, we employed Principal Component Analysis (PCA) and K-means cluster analysis to reduce data dimensionality and identify technological clusters of particular artifacts. For end-products that need to be compared morphologically, we used the Zingg classification system to yield effective visualizations.

Here, PCA was chosen as a basic solution for data processing. PCA has become one of the most widely used statistical methods in many fields, focusing on dimensionality reduction of datasets, especially for multivariate data (Pearson, 1901; Hotelling, 1933; Jackson, 1991). In archaeological research, PCA has become an essential quantitative analysis for high-dimensional data where numerous attributes are recorded from individual artifacts (e.g. Wilczek *et al*., 2014; Braun *et al*., 2019; Badawy *et al*., 2022). To apply PCA effectively, we first selected and measured different sets of variables according to specific artifacts and research objectives. For example, flakes were measured with fewer attributes than cores due to their simpler technological characteristics. We then collected lithic attributes such as size, platform angle, platform size, scar number, scar size, etc., integrating them into a dataset. Once compiled, we applied PCA to reduce the dataset to two principal components, allowing for clearer comparisons of technological characteristics and similarities.

With initial dimensionality reduction having been conducted through PCA, K-means clustering was applied, serving as an effective follow-up method for uncovering hidden characteristics within the data (Baxter, 1994; Everitt *et al*., 2001). By grouping data points into distinct clusters based on their attributes, K-means reveals similarities among individuals and offers an alternative perspective for examining and validating characteristics beyond those identified through techno-typological assessment.

In addition to the application of dimensionality reduction and clustering methods, Zingg classification was conducted to describe reduction products' morphology distribution. The Zingg system is a shape classification method based on linear measurements, originally devised for describing the shapes of geological clasts (Zingg, 1935; Uthus *et al*., 2005; Szabó and Domokos, 2010), though it has more recently been used to describe archaeological assemblages (Marwick *et al*., 2017). Any single item has three dimensions, namely the longest axis (geometric length, denotes to a), the second longest axis (geometric width, denotes to b), and the third longest axis (geometric thickness, denotes to c). The Zingg system uses two proxies, the elongation ratio and flatness ratio, to evaluate the general form of artifacts (Figure 2). The elongation ratio is b/a (denoted by p), and the flatness ratio is c/b (denoted by q). By combining two indices, a form factor (q/p) is generated, which, when visualized on a scatterplot, can be classified into four morphologies: blades, discs, equidimensional, and

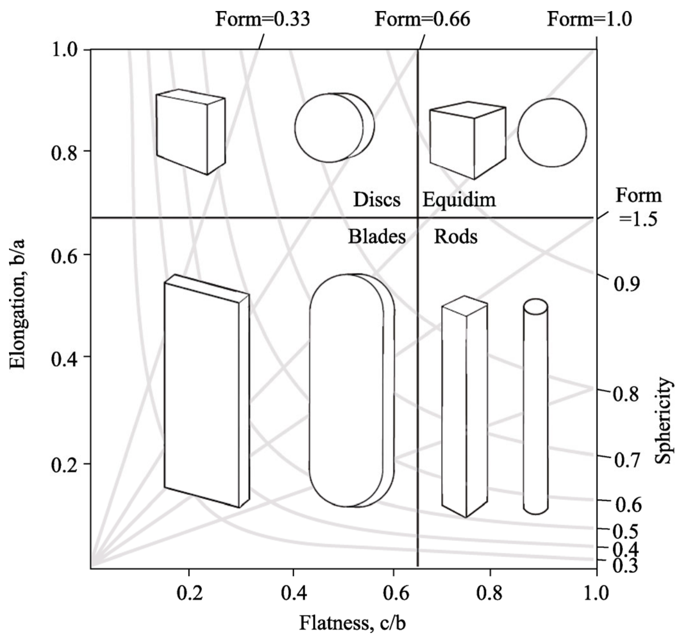

Figure 2 Schema of Zingg classification method (Marwick *et al*., 2017). The horizontal axis represents the flatness ratio, while the vertical axis represents the elongation ratio. Two additional axes at the value of 0.66 divide the space into four quadrants, corresponding to four morphological categories: blades, discs, equidimensional, and rods.

rods (Figure 2). Based on this classification and the Zingg diagram, we can more readily recognize the morphological patterns of artifacts, which is useful for describing the shape distribution of lithic assemblages.

3 Results

3.1 Fodongdi

A total of 9727 lithic artifacts were recovered from Fodongdi. Based on a comprehensive assessment of the patterns of raw material selection, reduction techniques, and tool production across the three phases of site occupation, the lithic artifacts were found to be variable in type and manufactured by diverse reduction techniques (Table 1) (Huan *et al*., 2024b). The techno-typological analysis shows that reduction products in the assemblage include freehand hard hammer percussion flakes, miniaturized bipolar pieces, and large cobble blanks made by bipolar percussion, including split cobbles and ridged hammer percussion flakes (RHP flakes) (Huan *et al*., 2024b). Miniaturized bipolar pieces are differentiated from other technique sequences through the exploitation of small quartz pebbles on the vertical long axis to produce relatively small and elongated splinters (Huan *et al*., 2024).

Table 1 Artifact classification, Fodongdi lithic assemblage (revised from Huan *et al*., 2024b)

Type	Phase A		Phase B		Phase C		Total	
	No.	%	No.	%	No.	%	No.	%
Freehand hard hammer percussion product	270	14.2	717	17.0	1519	42.1	2506	25.8
Bipolar percussion products on pebbles	152	8.0	192	4.5	112	3.1	456	4.7
Bipolar reduction products on cobbles	23	1.2	18	0.4	50	1.4	91	0.9
Tool	58	3.0	54	1.3	137	3.8	249	2.5
Stone hammer	11	0.6	5	0.1	12	0.3	28	0.3
Stone anvil	2	0.1	1	0.0	4	0.1	7	0.1
Chunk	554	29.2	1074	25.4	1285	35.6	2913	29.9
Shatter	794	41.9	2139	50.7	439	12.1	3372	34.7
Manuport	34	1.8	21	0.5	50	1.4	105	1.1
Total	1898	100.0	4221	100.0	3608	100.0	9727	100.0

A total of 456 miniaturized bipolar pieces were identified. The miniaturized bipolar pieces are the smallest reduction products in the assemblage, with an average length and width of 23.6 mm and 16.6 mm, generally having a small and relatively elongated shape but varies (Figure 3a). For comparison, split cobbles, the largest reduction products in the assemblage, have an average length of 89.4 mm and width of 57.8 mm (Huan *et al*., 2024b); the freehand hard hammer percussion flakes are slightly larger and show considerable size variation, with an average length of 27.4 mm (ranging from 7.5 mm to 91.5 mm) and an average width of 31.1 mm (ranging from 5.6 mm to 132.2 mm). Among the 456 miniaturized bipolar pieces, 49.8% have a length-width ratio over 1.5, and 17.3% have a ratio over 2 (Figure 3b). Correspondingly, elongated examples also have more parallel and longer effective edges.

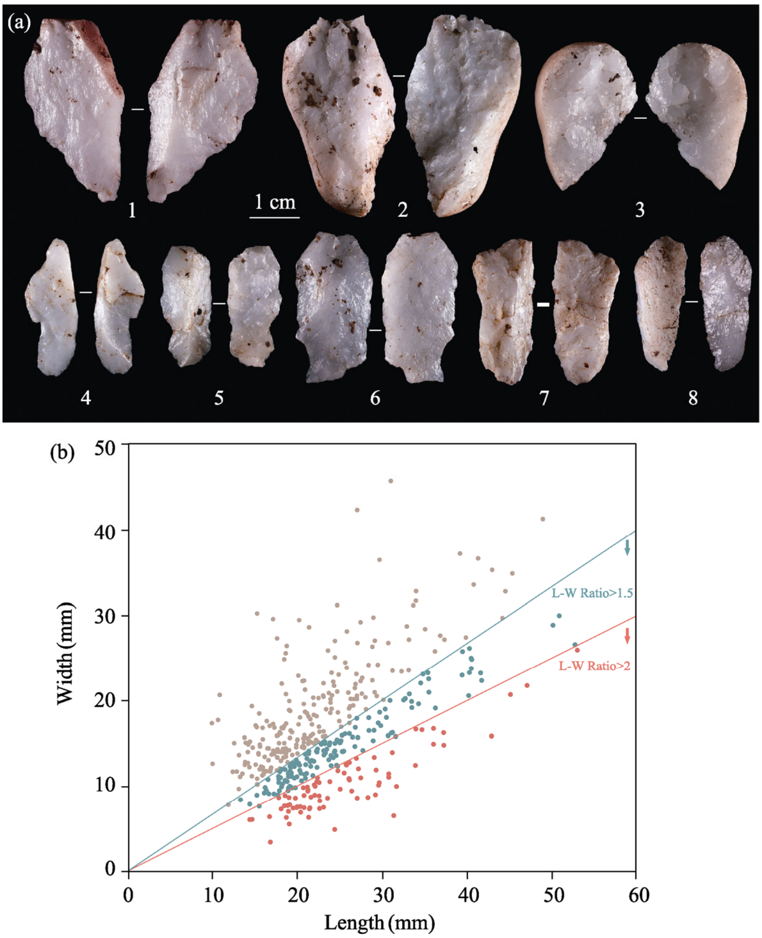

Figure 3 Miniaturized bipolar pieces and their length-width ratio at Fodongdi (a. selected bipolar products; b. distribution of all bipolar products shown by length and width values)

Miniaturized bipolar pieces account for 8.9%, 4.7%, and 3.3% of the assemblage respectively in the three cultural phases (A-C) (Figure 4), indicating a more important role in the early phase of site occupation. Their frequency is highest in phases A and B, while in phase C, which has a longer time span, their quantity decreased.

To further investigate the size distribution among different reduction products and assess the degree to which the miniaturized bipolar lithics represent an intentional artifact type, we performed a PCA followed by K-means clustering. The analyses were based on dimensional attributes (length, width, and thickness) for all reduction products. Figure 5 shows that the four most abundant types of reduction products are distinguishable within the PCA space, with artifacts grouped into different clusters. The clustering solution was determined using the elbow method (Tibshirani *et al.*, 2001), supplemented by visual inspection of multiple iterations with varying cluster numbers, with three clusters found to be the optimal number. The loading vectors and bar charts in Figure 5 display the contribution of each variable, showing that length predominantly influences Dim 1 (82.3%), while width is the primary contributor to Dim 2 (15%). Although some degree of overlap exists, bipolar pieces (shown in purple) primarily belong to cluster 1, displaying the lowest variability and forming the

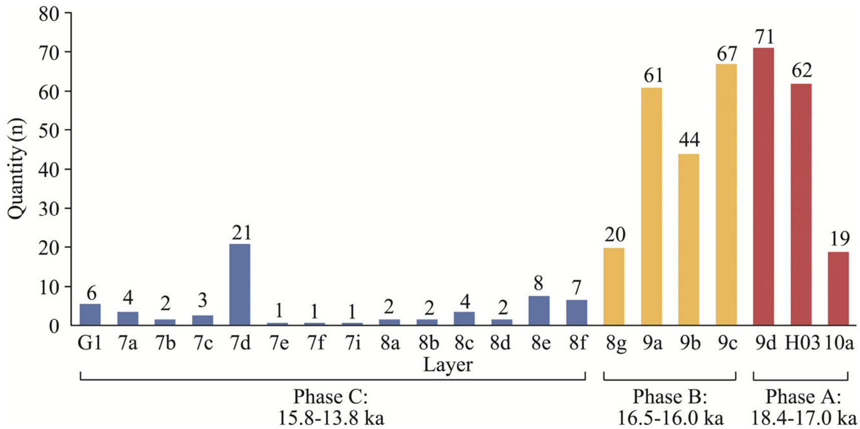

Figure 4 Distribution of miniaturized bipolar pieces by layer and phase at Fodongdi

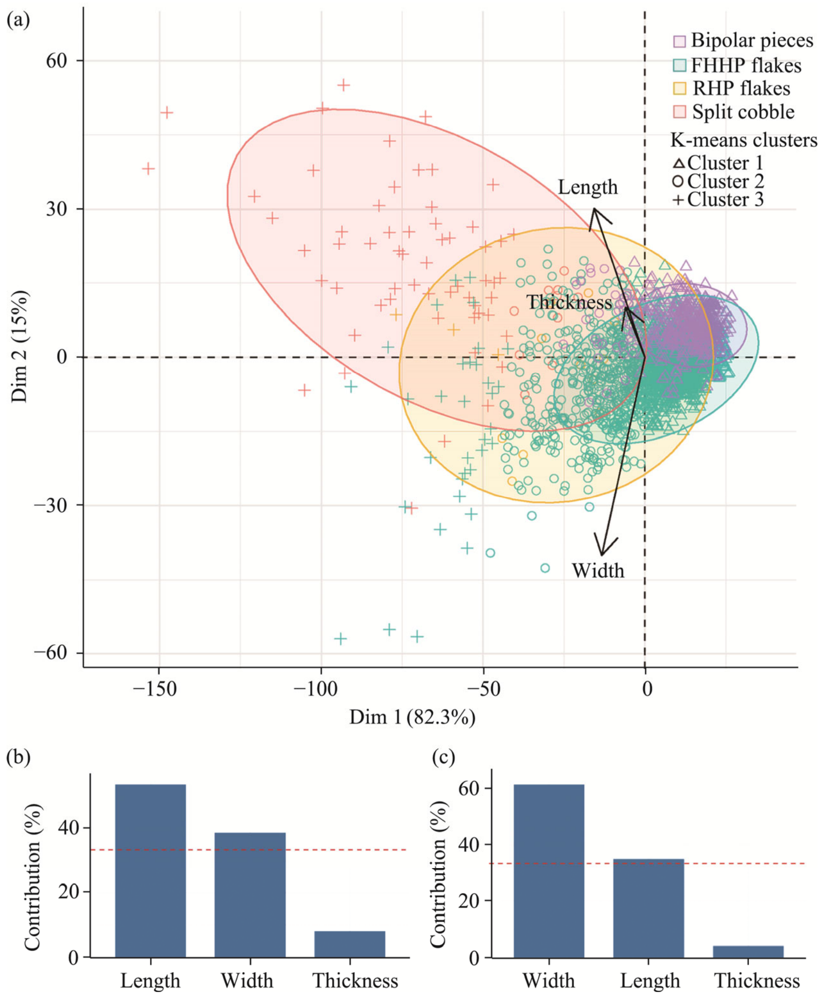

Figure 5 (a) Biplot of the Principal Components Analysis (PCA) and k-means cluster result of reduction products in the Fodongdi assemblage. The arrow represents the factor loadings; (b) Contributions of each variable to Dim 1; (c) Contributions of each variable to Dim 2. The red dashed lines on the bar charts indicate the expected average contribution. Variables with contributions larger than this cutoff could be considered as important in contributing to the component

most concentrated group among all types, with their distribution mainly in the first quadrant. This pattern may reflect their relatively uniform sizes, suggesting a potentially more constrained design and production system.

3.2 Fulin

More than 5000 lithic specimens were recovered from Fulin site through two excavations in 1972 and 2009–2010 (Zhang, 1977; SPCRARI and HCACR, 2020). Here we examine 1940 lithics recovered from the excavation of 1972, curated in the Institute of Vertebrate Paleontology and Paleoanthropology.

Our previous study (Huan *et al.*, 2023) identified hard hammer percussion products, bipolar percussion products, tools, chunks, and debris, composing a diverse lithic assemblage (Table 2). Among the reduction products, flakes and flake cores are the dominant products, accounting for 82.8% of the whole assemblage, including 1498 flakes and 108 cores; bladelet-like pieces account for 11.4% of the assemblage, including 190 bladelet-like pieces and 32 cores for bladelet-like pieces; bipolar splinters are also identified, but both the quantity and quality are limited (Huan *et al.*, 2023).

Table 2 Artifact classification, Fulin lithic assemblage (revised from Huan *et al.*, 2023)

Class	No.	%	Class	No.	%
Hard hammer percussion products	1823	94.0	Bladelet-like pieces	5	0.3
Flake cores	108	5.6	Tools	90	4.6
Flakes	1498	77.2	Stone hammer	3	0.2
Bladelet-like cores	32	1.7	Chunks	10	0.5
Bladelet-like pieces	185	9.5	Debris	3	0.2
Bipolar percussion products	11	0.6	Total	1940	100
Bipolar splinters	6	0.3			

Techno-typological analysis of the bladelet-like pieces indicates that hard hammer percussion and bipolar percussion could account for their production (Table 2). However, the majority were likely produced by hard hammer percussion based on the presence of distinct bladelet-like cores (Figure 6). The bladelet-like cores are usually in wedge-like shapes, with a wide, plain striking platform and a primary reduction surface situated in the front, where there is always a natural ridge for initiating reduction (Figure 6, 1–4). In contrast, normal flake cores in the hard hammer percussion system show less standardization. Their flaking utilizes available natural striking platforms, with reduction surfaces that are broader rather than ridge-like, thereby lacking the control typically provided by ridged areas (Figure 6b, 12–15).

The bladelet-like pieces show an elongated shape with parallel or subparallel edges, and some of them possess dorsal ridge which could serve as the guiding ridge during percussion. Their sizes are extremely small with an average length and width of 16.6 and 7.8 mm, and with an average length-width ratio of 2.19. The characteristic small sizes with their elongated shapes make them quite similar to bladelets in terms of morphology (Figure 6, 5–11). In contrast, normal flakes are much shorter and wider with average length and width of 14.3 mm and 13.1 mm and are more random in shape and size, which makes them unqualified to be considered as miniaturized lithics (Figure 6b, 16–19).

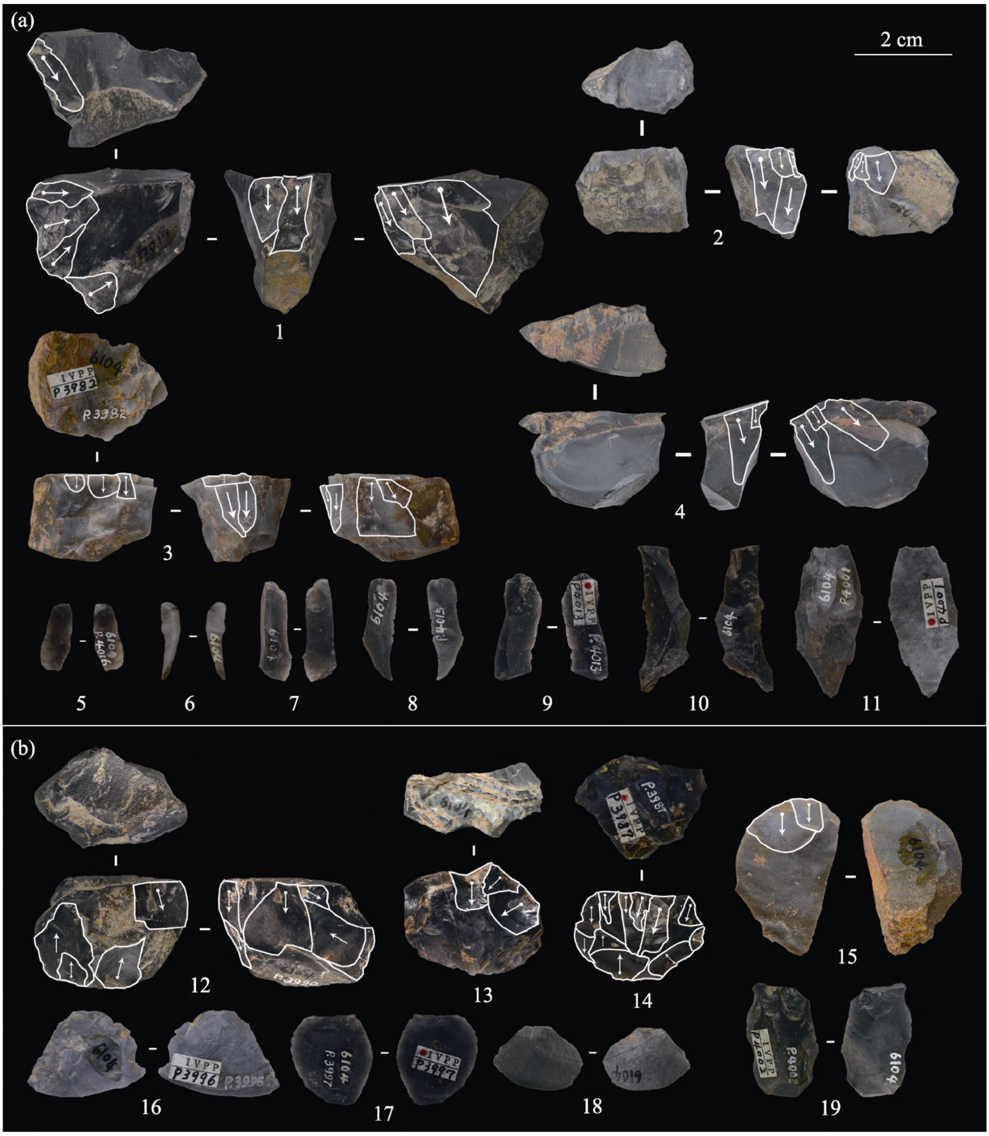

Figure 6 Selected reduction products from Fulin (a) 1–4, bladelet-like core; 5–11, bladelet-like piece; (b) 12–15, flake core; 16–19, flake

A key question for the Fulin assemblage is the distinction between normal flakes and bladelet-like pieces, as both of them are the product of hard hammer percussion. To investigate this question, we carried out a PCA and K-means cluster analysis based on the dimensional data (length, width, thickness). The clustering was conducted using the elbow method, and the result shows that three clusters are the optimal number based on the characteristics of data. The bar charts display the contribution of each variable, showing that length influences Dim 1 (82.8%), while width is the primary contributor to Dim 2 (15.3%). Flakes and bladelet-like pieces are distributed in different parts of the graphic, and are composed of various clusters, indicating a difference between flakes and bladelet-like pieces (Figure 7).

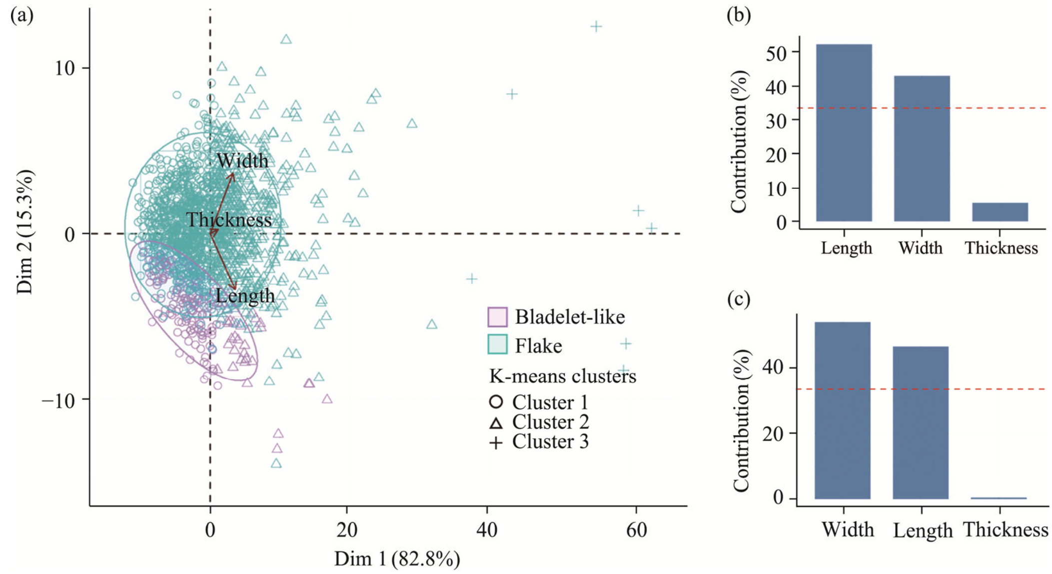

Figure 7 PCA and k-means cluster of reduction products from Fulin (a. PCA and k-means cluster analysis results; b. bar chart of contributions of each variable to Dim 1; c. bar chart of contributions of each variable to Dim 2)

To further evaluate the elongation of the bladelet-like pieces and compare the shapes of the two different products, we applied the Zingg classification system based on intact bladelet-like pieces and flakes to summarize the artifact form (Uthus *et al.*, 2005; Marwick *et al.*, 2017). The results indicate that bladelet-like pieces and flakes exhibit distinct distributions (Figures 2 and 8). In the "Blades" area of the Zingg plot 323 artifacts were identified, including 159 bladelet-like pieces (99.4% of all bladelet-like pieces) and 164 flakes (12.1% of all flakes). In contrast, the "Disc" area contains 678 artifacts, all of which are flakes (50.1% of all flakes), while an additional 37.3% of flakes fall beyond the coordinate system, above the "Disc" area. By combining these results, we visualized the distinction using red and blue markers to represent the two types. Figure 8 shows that the bladelet-like pieces are clearly located in the "Blades" area of the Zingg system, whereas the flakes are distributed over a much wider area, demonstrating a disc-like shape or wide shape instead of an elongated shape. This visualization supports the natural separation of bladelet-like pieces and flakes.

3.3 Xiqiaoshan

Archaeological investigations at localities 4 and 18 at Xiqiaoshan recovered more than 20,000 lithic artifacts (Zeng and Li, 1988). Here we analyze 559 lithic artifacts from localities 4 and 18 curated at Sun Yat-sen University. The collection contains varied types, including microblade cores, microblades, flakes, tools, chunks, and bipolar splinters (Table 3).

Microblade technique products are the major characteristic of this collection, and 343 microblade cores and 44 microblades were identified (Figure 9 and Table 3). Microblade cores include 334 intact flaked cores, five core fragments, and four prepared blanks. The microblade cores can be categorized into wedge-shaped, conical, semiconical, and irregular cores, which are the four principal morphologies (Figure 9, 1–8). Their general size is quite

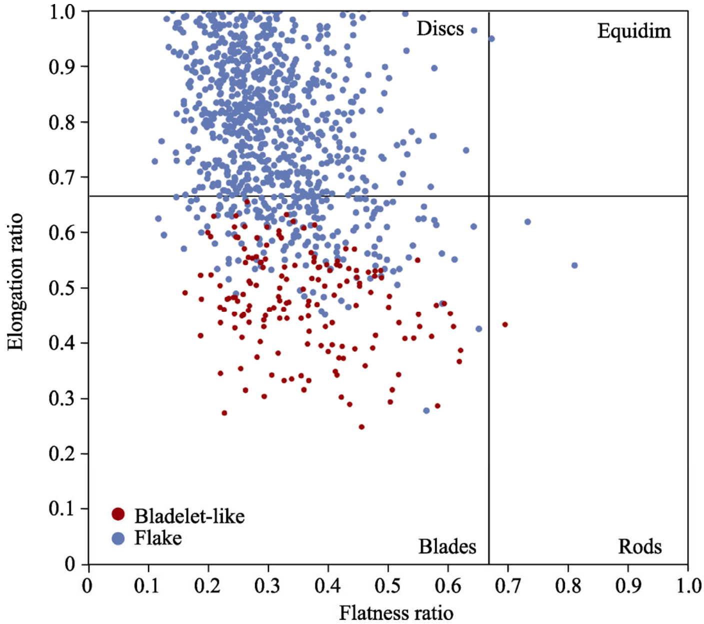

Figure 8 Zingg classification of reduction products from Fulin. To highlight different types, we marked the bladelet-like samples in red and marked the flake samples in blue

Table 3 Artifact classification, Xiqiaoshan localities 4 and 18

Type	No.	%	Type	No.	%
Microblade cores	343	61.4	Broken microblades	2	0.4
Intact cores	334	59.8	Flakes	104	18.6
Core fragments	5	0.9	Bipolar splinter	1	0.2
Prepared blanks	4	0.7	Tools	47	8.4
Microblades	44	7.9	Chunks	20	3.6
Intact microblades	42	7.5	Total	559	100.0

small with an average height (from platform to distal bottom), width, and thickness of 30.3, 29.7, and 21.0 mm (Yang *et al*., 2022). Among the 44 microblades, two broken and 42 intact ones were identified, including six crest microblades (Figure 9, 9–14). Their average length and width are 24.0 and 9.9 mm, with a length-width ratio of 2.41. They show a small size, a significantly elongated morphology, parallel edges, and regular dorsal ridge. This collection contains microblade technique products from different reduction stages and exhibits a complete microblade production procedure.

Techno-typological study of the collection established a microblade reduction strategy, illustrating the production of varied core types including wedge-shaped, conical, semiconical, and irregular (Figure 10). This production begins with selecting local chunk blanks and proceeds with one of the following three main reduction routines:

(1) Direct reduction on suitable natural platforms, in which case the irregular, conical, and some semiconical cores are produced;

(2) Selection and preparation of a platform for consequent reduction, usually resulting in wedge-shaped cores;

Figure 9 Selected microblade and microblade cores excavated from Xiqiaoshan. 1, 2, 5: Wedge-shaped core with double platforms; 3, 4, 6, 7: Wedge-shaped core; 8. irregular core; 9: Crest microblade; 10–14: Microblades

(3) Selection of suitable flakes as blanks for further reduction, resulting in microblade cores on flakes; flake blanks may be turned into microblade cores by exploiting the flake-platforms directly as microblade-core platforms, otherwise, new platforms need to be prepared.

In the maintenance stage, a key feature of Xiqiaoshan microblade reduction is the extensive development of multi-platforms and reduction surfaces, especially on wedge-shaped cores. In total, 60 wedge-shaped cores bear evidence of changes or rejuvenation of platforms, accounting for 17.5% of the microblade cores.

To evaluate microblade core features in detail, PCA and K-means clustering based on multiple measurements were conducted (Figure 11). Each point corresponds to an individual artifact, with colors indicating distinct clusters classified through K-means. The optimal number of clusters was determined using the elbow method. Although some overlap is observed—particularly between type B and type C—this is expected given the continuous nature of lithic morphological variation. Despite this, clear distinctions can still be noted, supporting the interpretation of technological differentiation. The bar chart illustrates the contributions of different variables to the two dimensions, showing that multiple attributes in-

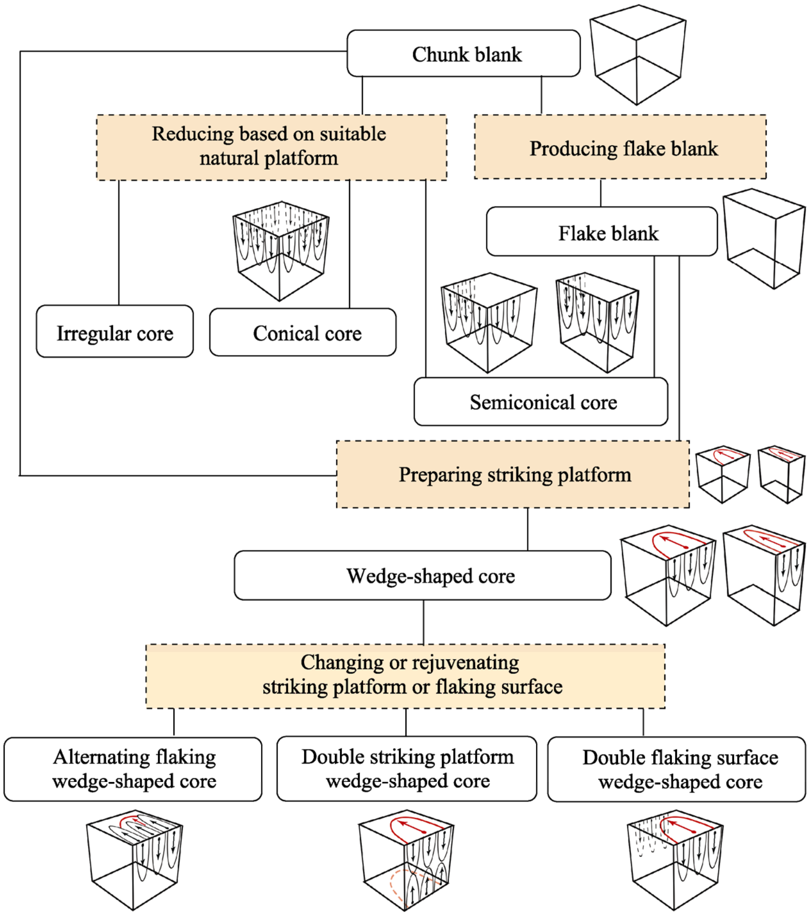

Figure 10 Reduction strategy schema of microblade cores from Xiqiaoshan. White bars are the name of the products, while yellow bars are the specific processing during production.

fluenced the classification results. Type A are massive in size but with relatively few removals as well as platforms; type B with more removals and platforms, but narrower in shape and smaller in size; type C have shorter heights (from platform to the distal end) and smaller platform angles, which mainly denote to wedge-shaped cores with extensive reduction by changing platforms.

4 Discussion

4.1 Lithic miniaturization and technological diversity

Combining techno-typological and quantitative analysis, we have presented results from three miniaturized lithic assemblages from South China. Although there is a disparity in the total number of lithic specimens among the three sites, the quantities of representative miniaturized lithics are relatively comparable (456 in Fodongdi, 222 in Fulin, and 387 in Xiqiaoshan). We have identified and reaffirmed microblade technology at Xiqiaoshan, oft-discussed in in North and northeastern China, and identified lithic miniaturization at Fodongdi and Fulin, composed of miniaturized bipolar pieces and bladelet-like pieces.

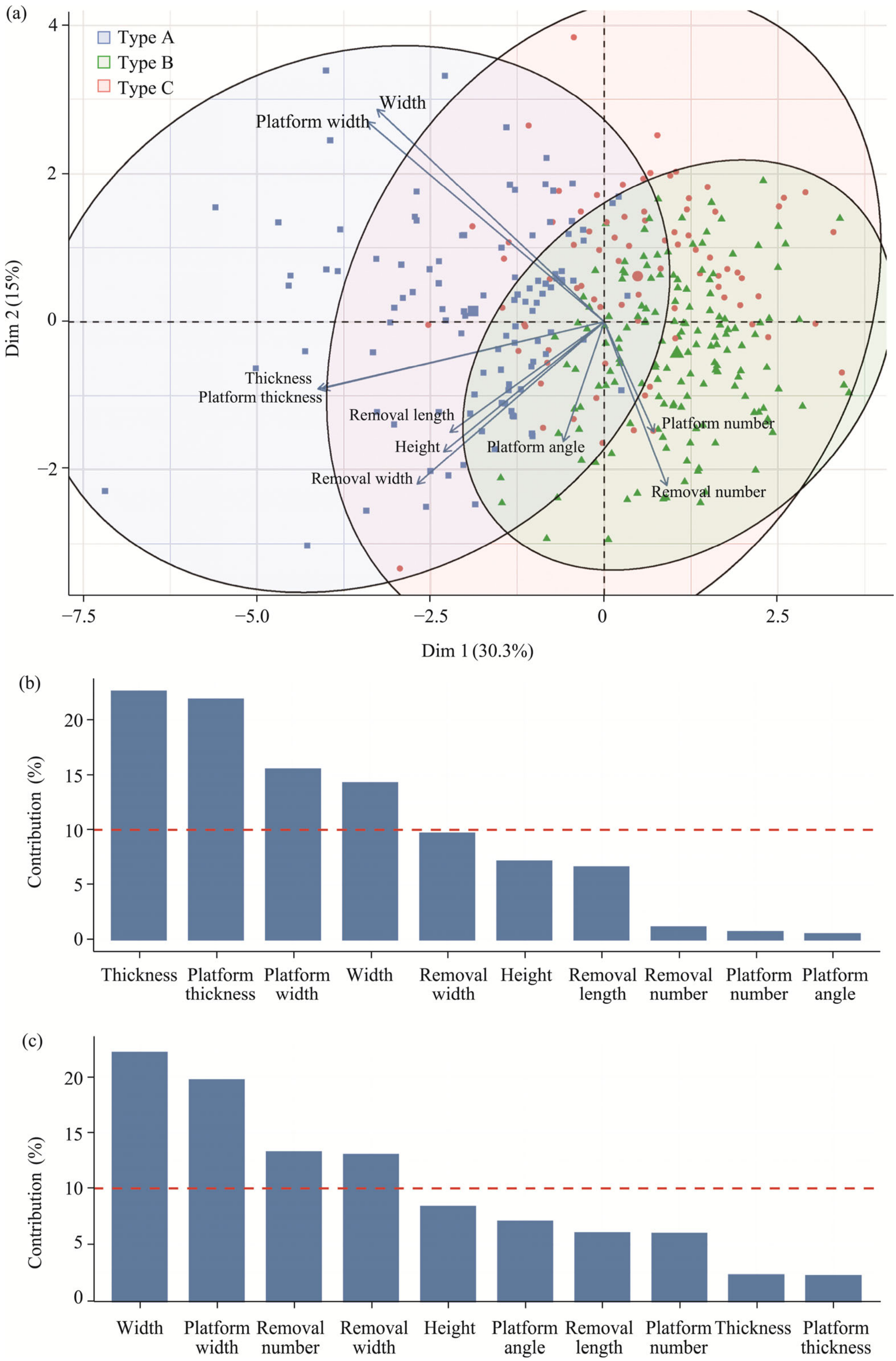

Figure 11 PCA and K-means results of microblade cores based on multiple measurements (a. Type A is blue, type B is green, and type C is red. The arrow represents the factor loadings; b. Contributions of each variable to Dim 1; c. Contributions of each variable to Dim 2)

Figure 12 presents a comparative analysis of the dimensions of representative miniaturized lithics from three sites. To account for the varying scales of different artifacts, both the x-axis (length) and y-axis (width) are plotted on a logarithmic scale. This transformation mitigates the effect of size differences across assemblages, allowing for a more balanced visual comparison. The plot highlights the clustering patterns of miniaturized bipolar pieces, bladelet-like pieces, and microblades, illustrating the variability in artifact dimensions across different sites. As the figure shown, miniaturized bipolar pieces from Fodongdi exhibit a larger size range, whereas bladelet-like pieces from Fulin display a more consistent distribution with generally smaller dimensions. Microblades from Xiqiaoshan also show a constrained distribution and have a more elongated morphology compared to their counterparts from Fodongdi and Fulin.

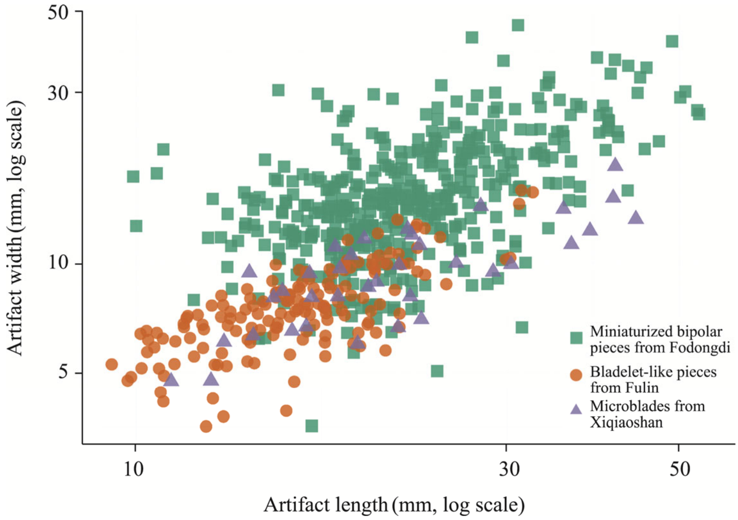

Figure 12 Comparison of dimensions of representative miniaturized lithics from three sites in a logarithmic scale

The three assemblages are dated to different phases of the late Pleistocene to the middle Holocene and show distinct technological systems (Table 4). There is a tendency towards a higher level of standardization over time. This observation is based on the presence of dorsal ridges, increased parallel morphologies, and a higher average length-width ratio. Although the assemblages belong to different technological systems, they share similar morphological traits as small overall sizes, small-thin-elongated pieces, and long cutting edges (Figure 13). In other words, the technologies of lithic miniaturization in South China included diverse technologies to obtain similar, desirable end-products.

Table 4 Technological comparison of representative miniaturized lithics across three sites

Site	Age (ka BP)	Type	Dorsal ridge	Morphology	Length-width ratio (avg.)	Technique
Fodongdi	18.4–13.8	Miniaturized bipolar pieces	Absent	Relative unparallel	1.58	Bipolar
Fulin	11.7–10.3	Bladelet-like pieces	Random	Subparallel	2.19	Direct percussion
Xiqiaoshan	7.8–5.6	Microblades	Present	Parallel	2.41	Pressure

Figure 13 Miniaturized reduction products from the three studied lithic assemblages (Upper: Fodongdi; Middle: Fulin; Bottom: Xiqiaoshan)

In addition to the assemblages reported here, examples of lithic miniaturization achieved by multiple technologies appear to be present at other sites in South China over this time range. At Huilongwan, Shanghu, and Dabanqiao, the bipolar technique was applied to produce elongated bipolar pieces, especially on the abundant vein quartz resources (Yang, 1993; SPCRARI and SH-CNU, 2021; Zhao *et al*., 2023). Bladelet-like pieces produced by direct percussion have been reported at sites such as Niupodong and Tangzigou (IA-CASS *et al*., 2015, 2017; Zhu *et al*., 2020). Microblade assemblages have been reported recently as several sites, such as at Guye, Liujiazhai and Zhongzipu (IA-CASS, 1991; SPCRARI *et al*., 2012, 2022; Deng and Liu, 2023; Huan *et al*., 2024a).

4.2 Implications for ecological adaptation and population dynamics

The prevalence of lithic miniaturization has been ascribed to variables such as environmental deterioration and low ecological carrying capacity (e.g. Kuhn, 1995; Elston and Kuhn, 2002), as has been suggested for microblade technology in North China and Northeast Asia since the Late Pleistocene (Yi *et al*., 2016; Wang, 2018; Yue *et al*., 2021; Zhu, 2023). Higher efficiency in raw material exploitation, longer effective edges, and increased portability of miniaturized lithics has been argued to be the product of coping mechanisms tied to harsher habitats (Bar-Yosef and Kuhn, 1999; Eren *et al*., 2008; Mackay, 2008; Muller and Clarkson, 2016; Pargeter and Shea, 2019; Low and Pargeter, 2020).

The period ranging from deglaciation to the middle Holocene in South China witnesses a general trend towards environmental amelioration (NGICP, 2004; Xiao *et al*., 2014a, 2014b, 2015, 2019; Zhao *et al*., 2021) (Figure 14a). Fodongdi, located at the tropical and sub-tropical region, human occupations spanned three climatic periods including the Last Glacial Maximum, Heinrich stadial 1, and Bølling-Allerød warming (Figure 14b). Stone tool technology and the quantity of bipolar artifacts changes in correspondence with these climatic shifts (Figure 4). Bipolar products were especially abundant during the early phases when the condition was relatively cool and dry. A possible decline in commonly used resources, particularly edible plants that were typically available in tropical-subtropical forests, may have led people to rely more on animal and aquatic resources (Xiao *et al*., 2015, 2019; Huan *et al*., 2024). In this case the occurrence of miniaturized bipolar pieces is consistent with the interpretation of lithic miniaturization as an adaptation to harsh environment. At Fulin, in the marginal area of the Qinghai-Tibet Plateau, miniaturized lithics, including bladelet-like pieces, were present during the harsh period of the Younger Dryas. This extreme cold event further intensified survival pressures, making the portability and efficiency of stone tools even more critical for hunting in mountainous regions with significant altitude variation. The contexts of Fodongdi and Fulin suggest that some of the miniaturized lithics in South China were a response to environmental challenges across ecological niches.

After the onset of the Holocene, the climate stabilized, and microblade technology makes its appearance in South China (Figure 14b). The increase in microblade production in this period may be related to climatic amelioration, as a series of transitions in lifestyle occur

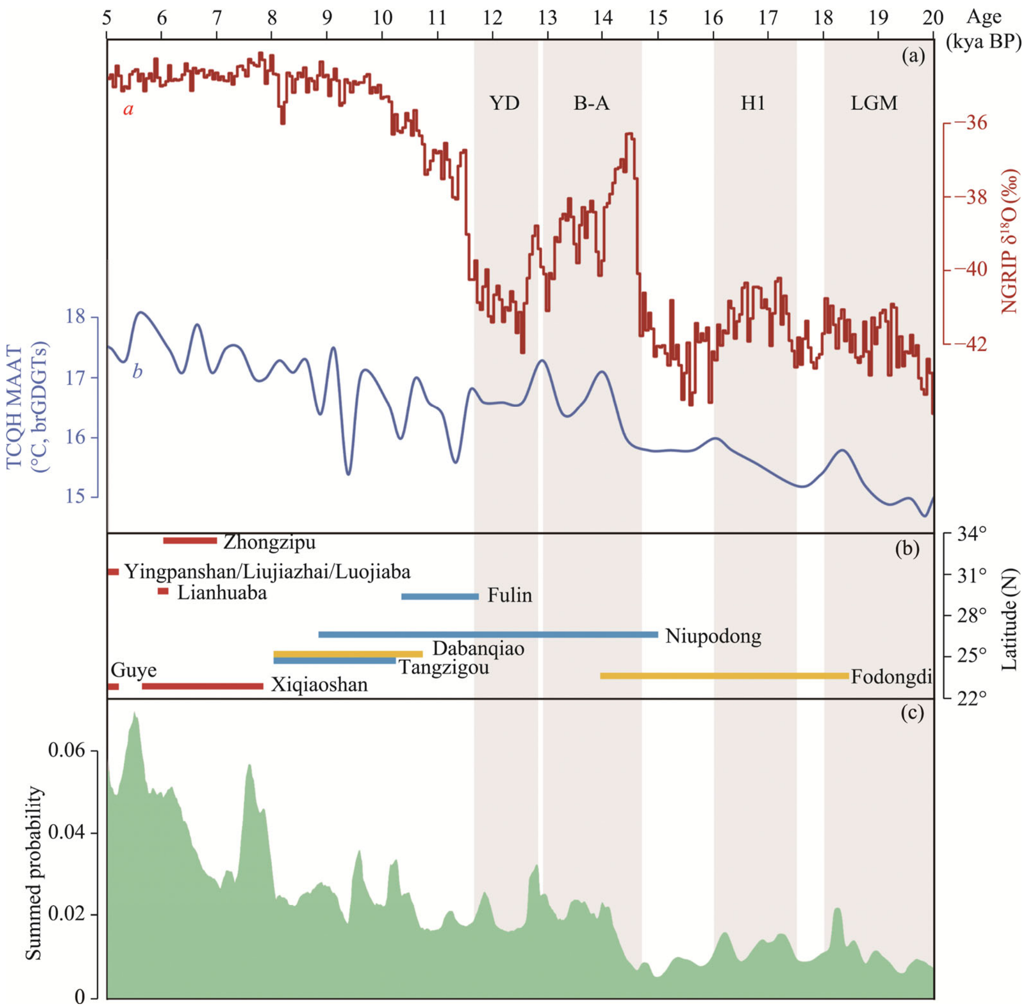

Figure 14 Temporal and spatial distribution of miniaturized lithic assemblages. The grey vertical bars denote climatic events discussed in the main text. (a) Global and local representative climatic proxies (a: NGICP, 2004; b: Zhao *et al*., 2021); (b) Miniaturized lithics can be categorized into three main types including miniaturized bipolar pieces (in yellow), bladelet-like pieces (in blue), and microblade (in red) (see detailed information of cited sites in Supplementary materials); (c) Summed probability distribution, South China.

during this time, such as a broader spectrum diet and increased sedentism (Liu *et al.*, 2010; Cohen, 2011; Zuo *et al.*, 2016; Deng *et al.*, 2022). For example, in coastal zones like Xiqiaoshan, transportable microblade tools may be adopted to meet the daily demand for exploiting intertidal and marine resources, as suggested in other coastal regions (Carlson, 1960; Sanger, 1968), reflecting broader patterns of coastal resource use observed worldwide (Marean, 2014; Arniz-Mateos *et al.*, 2024; García-Escárzaga *et al.*, 2024). Given this evidence, it appears that miniaturized lithics are part of a flexible adaptive strategy, allowing for adaptations to a variety of environmental situations.

While changes in ecological contexts can be associated with lithic miniaturization, other factors may also have influenced technological choices. Our summed probability distribution analysis, based on 1329 radiocarbon dates from archaeological sites in South China, suggests that population dynamics could be another potential factor (Wang *et al.*, 2014). Figure 14c shows that just after the middle Holocene, microblade assemblages increased as the estimated population rose dramatically. Naturally, their relationship is complex and requires further evidence, but the emerging trend suggests that population dynamics may be a noteworthy contributing factor. Here, lithic miniaturization could be a solution to population pressure in South China, a correlation that has been noted elsewhere (Petraglia *et al.*, 2009; Bousman and Brink, 2018). Moreover, as a technology long prevalent in northern China, microblade technology provides direct evidence of cultural influence from the north. Additional evidence, such as records of ancient DNA, crops, and pottery, further supports the southward diffusion of northern material culture and populations during this period (Yang *et al.*, 2020; Dai *et al.*, 2021; Huan *et al.*, 2022; Ren and Chen, 2022).

5 Conclusion

Miniaturized lithics in South China have long been under-played in examining technological developments through time. The current study focused on miniaturized lithic assemblages of South China, shedding light on a key technological and evolutionary pattern in this region, which is more sophisticated than previously realized. We suggest that lithic miniaturization and its diverse technological forms associates with the adaptations of human populations over time, likely relating to fluctuating climatic conditions and population dynamics. The current study invites us to consider the significance of this form of technology and its role during the development of societies in South China. We look forward to additional technological studies and multidisciplinary research around this noteworthy cultural phenomenon.

Declaration of competing interest: The authors declared that we have no conflicts of interest to this work.

Data availability: All artifacts referred to in this study are curated in the Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, the Yunnan Institute of Cultural Relics and Archaeology, Kunming, and at the Museum of Sun Yat-sen University, Guangzhou. All studied data are included in this article or in the supplementary materials. Raw data and R code for the stone artifact analysis are openly available at Zenodo: https://doi.org/10.5281/zenodo.13958749.

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