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RESEARCH

Lithic technologies at Guanyindong cave, Southwest China: diversity and innovation during the Chinese Middle Palaeolithic

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Abstract

There is a long-standing view of Chinese Palaeolithic that lithic industries with pebble-tools and simple core-and-flakes are prevalent, without innovations and technological changes until the advent of the Upper Palaeolithic. However, with new discoveries and reassessments of previous archaeological materials, many doubts have been raised on the tenableness of this view. Preceding reports of the Levallois concept at Guanyindong revealed the presence of an early prepared core technology in East Asia. To further contribute to this issue, here we present a comprehensive study of the whole Guanyindong assemblage. Our results found that Levallois stone-tool technology is not the only skill acquired by Guanyindong knappers. Instead, systematic Middle Palaeolithic techno-complexes, including multiple flaking strategies, diverse tool types, and formal tool manufacture, suggest that Guanyindong industry is indeed a Middle Palaeolithic technological complex that is comparable with West Eurasia and Africa, challenging the previous understanding of Palaeolithic industries pre-40 ka in China as static and conventional.

Keywords Chinese Middle Palaeolithic · Guanyindong · Lithic techno-complex · Southwest China · Late Middle Pleistocene

Introduction

The late Middle Pleistocene witnessed the transition from Lower Palaeolithic to Middle Palaeolithic (MP) in West Eurasia and Africa (Early Stone Age to Middle Stone Age) and in many areas included substantial milestones in human evolution, such as the replacement of *Homo erectus*/*Homo heidelbergensis* by *Homo sapiens* and other species (Harvati et al. 2019; Hublin et al. 2009, 2017; Jacobs et al. 2019). From a technological perspective, Levallois lithic technology is often recognized as the hallmark of the MP (McBrearty and Brooks 2000; Monnier 2006; Tryon et al. 2005). In addition to Levallois, shifts to a variety of flake reduction systems and flake tools, replacing large cutting tools (LCTs) and core tools, are also important parts of the MP technological complex (Dibble and McPherron 2006; Kuhn 2013; Tryon and Faith 2013). They are almost as indicative as the Levallois concept in representing MP technological changes. These technological systems reflect changes among MP hominins from their ancestors in, for example, cognitive, social, and adaptive behaviors, demographic growth, and expansion of hunting and resource territories (Berna and Goldberg 2007; Kuhn 2013; Shennan 2001).

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However, these substantial technological revolutions have so far mostly been found and reported in West Eurasia and Africa (Fontana et al. 2013; Goren-Inbar 2011; Tryon et al. 2005). MP technological innovations in East Asia have long been considered as static or less conspicuous. Recently, doubts have been raised about the soundness of this hypothesis as more studies have reported assemblages associated with technological diversity in China during the Lower Palaeolithic and MP (Hu et al. 2019c; Li et al. 2019b; Ma et al. 2024; Wang et al. 2021; Yang et al. 2021). Moreover, organized Levallois technology from the Guanyindong site, southwest China (Hu et al. 2019b, 2023a) further challenged the monotonousness, and ignited debate over technical innovations in this region (Hu et al. 2019a; Li et al. 2019a, d, 2020). To contribute that, here we present the results of a systematic study of the whole lithic assemblage presently available from the same site - Guanyindong cave, further revealing diverse flake production strategies and tool curation that denote the MP behaviors in contemporary East Asia.

The Guanyindong site (26°51′26″N, 105°58′7″E, a.s.l. 1464 m, Fig. 1a), located in Qianxi city, Guizhou Province, is a limestone cave site extending from east to west. This region is characterized by typical karst landscape (Fig. 1b), with a general elevation of 1400–2000 m. The main climate of this area is subtropical humid, with evergreen

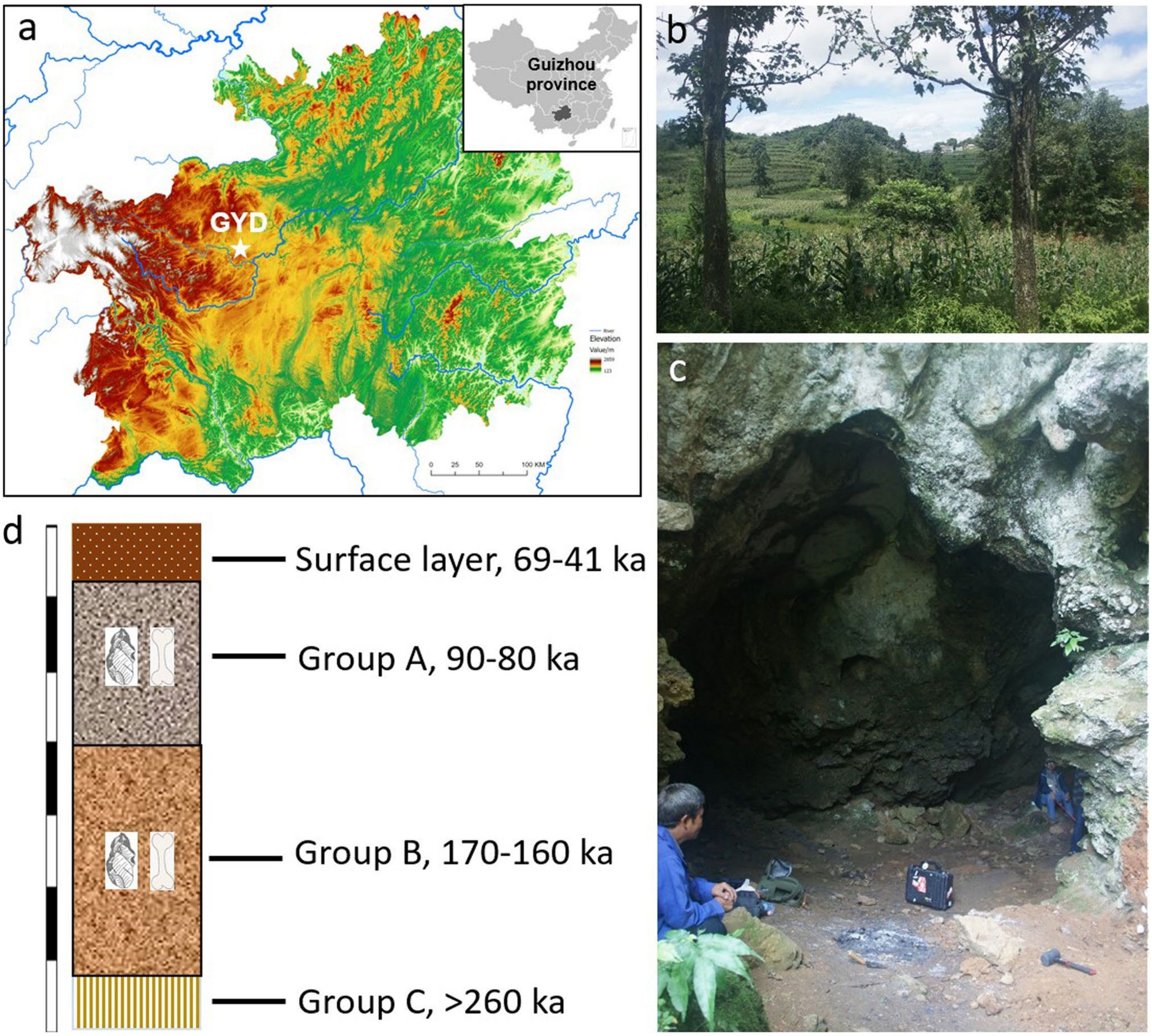


Fig. 1 (**a**) Location of the Guanyindong cave site (GYD); (**b**) Modern landscape in front of west cave entrance that covered by vegetations; (**c**) West cave entrence; (**d**) Schematic diagram of strategraphy and luminescence dating results (Hu et al. 2019b)

broad-leaved forest, coniferous and broad-leaved mixed forest, and montane elfin forest. It was discovered in 1964 by a team organized by the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP), Chinese Academy of Sciences, and the Museum of Guizhou province. A total of four excavations were conducted in 1964, 1965, 1972 and 1973, yielding over 3,000 stone artefacts and abundant mammal fossils. The main excavation was conducted in 1970s at the west cave entrance (Fig. 1c), where most of fauna fossils and stone artefacts were found (Li 1986).

According to the excavation reports by original excavators (Li 1986; Pei et al. 1965), the stratigraphy of the sediments at the west cave entrance was divided into 9 layers (Layers 1–9) and 3 groups (Fig. 1d): Group A (Layer 2), Group B (Layers 3–8) and Group C (Layer 9). There are 879 stone artifacts recovered from Group A, and 1,444 from Group B. Unfortunately, after being stored for several decades and transported several times, only a small amount of the stone artefacts (117 pieces from Group B, and 87 from Group A) contains provenance information. Previous studies conducted by both Li (1986, page 161–163) and Hu et al. (2019b; SI-Chronological change in the lithic assemblage section) show that there is no major techno-complex changes over time. Luminescence dating, conducted on samples collected from the west cave entrance, provided a firm constraint on the sedimentary ages of the artifact-bearing deposits: Group A was ranging from 90 – 80 ka, while Group B ranged from 170 – 160 ka. Additional luminescence dating on samples collected from inner chambers confirmed a continuous occupation period, spanning from 180 to 80 ka (Hu et al. 2023b). In this paper, we will treat all stone artifacts as an integral part of the MP in its entirety. Since that the occupation period (180 – 80 ka) falls within the conventional western MP timespan (~ 300 – 45 ka), this approach does not affect or alter the interpretation of MP at Guanyindong.

In previous studies of lithic industries, Pei et al. (1965) concluded that the Guanyindong industry possesses a different Palaeolithic culture from either China or Europe. After all excavation seasons were finished, thorough studies mainly focused on typology and statistical analysis were conducted (Li 1986), specifically demonstrating the entire industry in detail. The studies summarized several aspects of the industry including full variety of raw materials, diversity in retouch approaches and typologies, a high degree of variability, and steep, uneven retouched edges. They believe that the Guanyindong industry should be assigned to a Lower Palaeolithic culture owing to the geochronology. Later, two studies were done on different aspects (Leng 2001; Li et al. 2009) – one study based on core typology and one on *chaîne opératoire*. Some scholars also indicated certain characters of the culture such as Levallois related features (Freeman 1977) and distinct features compared with north China (Jia and Huang 1985; Li 1993; Zhang and Cao 1980). Given those studies were carried out several decades ago by different scholars with different perspectives and interests, we started this study believing valuable technological information can still be gained from them using more recently-developed analytical approaches.

Materials and methods

Here we report our re-examination of 2,211 artifacts that were mainly recovered from the west cave entrance, during the first three excavations carried out in 1964, 1965, and 1972 (Table 1). These artifacts are stored in the Collection House of IVPP. The fourth excavation was conducted by the Museum of Guizhou province, yielding about 800 stone artifacts (Li 1986; Page 154), which were stored in the Museum of Guizhou Province and are not included in the current study. The original report from the 1986 documented 2,323 stone artifacts stored at IVPP. Later, around 2009, Li (2009) reported 2,280 stone artifacts. Our initial observation counted 2,273 (Hu et al. 2019b), and the current data stands at 2,211. All of these counts are based on artifacts collected during the first three excavation seasons from 1964 to 1972 and are now housed at IVPP. Our team made multiple visits to IVPP for data collection. The data published in 2019 was gathered during the years 2016 and 2017, while the data for the current paper was collected in October 2018. During the visit of 2018, a thorough re-evaluation of available stone artifacts was conducted, building upon the information obtained from our initial two visits. Our reassessment process reaffirmed the majority of our initial observations. However, certain adjustments were inevitably made to some individual specimens comparing with the previous paper (Hu et al. 2019b). Most of these adjustments come from revisions on classifications of many specific stone artifacts, resulting in slight variations in quantities among cores, flakes, and retouched pieces as well as their corresponding metric characteristics.

During our initial investigation of the artifacts depicted in Fig. 19, for instance, we primarily focused on identifying and distinguishing between dentated and smooth edges (for example, Fig. 19c, and d), inadvertently neglecting the overall configuration of the tools. Upon re-evaluation, we observed that these tools exhibit commonalities and may potentially indicate specific tool types that were previously overlooked. Regarding Fig. 19-a, and b, the initial classification as convergent scrapers, which can often be indistinguishable from points (Debénath and Dibble 1994), have been reassigned to elongated-pointed pieces. This reassignment is based on our observation that these specific retouched artifacts exhibit common features such as elongated pointed techno-morphology and deliberated butt

Table 1 Assemblage categories and proportions by raw materials of Guanyindong site

type	chert		basalt		limestone		others		total
	count	%	count	%	count	%	count	%	
cores	208	83.9	2	0.8	38	15.3			248
Levallois core	9	81.8			2	18.2			11
discoidal core	9	90			1	10			10
core-on-flake	51	82.3			11	17.7			62
volumetric core	11	91.7					1	8.3	12
other core type	127		2		24				153
complete flakes	139	74.6			46	24.3	2	1.1	189
flake breaks	6	100							6
Chunk & debris	569	74	8	1	190	24.7	2	0.3	769
retouched chunks	43	76.8			13	23.2			56
retouched flakes & breaks	736	78	10	1.1	192	20.4	5	0.5	943
backed knife	5	71.4			2	28.6			7
beak	6	85.7			1	14.3			7
borer	47	73.4			17	26.6			64
burin	5	83.3			1	16.7			6
chopper	1	50	1	50					2
cleaver	1	100							1
denticulate	53	69.7	1	1.3	21	27.6	1	1.3	76
End-scraper	30	83.3			6	16.7			36
natural backed	3	60			2	40			5
notch	68	86.1	1	1.3	10	12.7			79
point	23	82.1			5	17.9			28
scraper	464	77.5	7	1.2	124	20.7	4	0.7	599
tanged point	8	88.9			1	11.1			9
unidentifiable	22	91.7			2	8.3			24
overall	**1,703**	**77**	**20**	**0.9**	**479**	**21.7**	**9**	**0.4**	**2,211**

retouching. Classifying them simply as denticulates or scrapers would obscure their underlying techno-complexity.

In this study, we employed standard terminology and concepts in lithics analysis (Andrefsky 1998; Debénath and Dibble 1994; Inizan 1999). Meanwhile, the entire lithic assemblage was examined through the application of technical analyses developed by specialists such as Geneste (1988), Boëda et al. (1993; 1990), Geneste et al. (1997) and Vaquero (2008), encompassing both qualitative and quantitative parameters. The qualitative method follows the general concepts of the *chaîne opératoire* (Bar-Yosef and Van Peer 2009; Geneste 1991; Pelegrin et al. 1988; Sellet 1993). The process includes the recognition of the raw material; the reduction strategies of cores; and the retouched or unretouched products (flakes, flake fragments, debris and chunks). The quantitative analysis mainly relies on metrical and morphometric data including basic statistics on artifacts dimensions and main attributes. For the chunks and debris, only mass was measured.

Regarding retouched pieces, it is important to note that many stone artifacts may have undergone post-depositional effects (Hu et al. 2019b; Li 2009). To ensure the integrity of our primary arguments, we have excluded visually apparent taphonomic marks from the lithic analysis. However, completely eliminating the impacts of post-depositional alterations is challenging due to the same patina and nature of MP tool curation. Nevertheless, our analysis is based on their definitive and/or primary characteristics. For instance, if a flake displays isolated, irregular, and discontinuous ‘retouch’ on the edge, we disregard these ‘retouches’ and ascribe the artifact as a flake. The same principle applies to both tools and cores.

Discoid production is defined as cores exhibit one or two flaking surfaces that are centripetally exploited along the periphery. The removals of discoidal conception are secant at the intersection between flaking surface and striking platform surface. Detachments are achieved by direct percussion using a hard hammer (Boëda 1995; Pasty 2000; Peresani 1998; Terradas 2003; Vaquero and Carbonell 2003). Core-on-flakes have been studied and discussed in a wide range of research (e.g. Brantingham et al. 2000; Dibble and McPherron 2006; Marwick et al. 2016; Mathias and Bourguignon 2020). Based on the general principles of those literatures, we ascribe the core-on-flake preliminarily to flakes that were recycled and showing removals (usually larger than 15 mm) mostly, but not always, on the ventral surface. The recognition of Kombewa flakes is associated with two bulbar residuals on the proximal end of both the ventral and dorsal surfaces (Owen 1938). Our diagnosis of volumetric exploitation is based on analytical approach described by Carmignani (2017). The main point of this core exploitation approach is its reduction follows the maximum length along the thickest part of a blank, systematically organized within the block's thickness. By specifically targeting the narrow frontal face of the core, precise control over debitage is achieved, obviating the need for core reshaping as volume reduction occurs continuously. The resultant end-products are distinguished by their elongated morphology. For this reason, volumetric exploitation cores are quite alike the blade and/or laminar production since both of them aiming produce long narrowed debitages (Delagnes 2000; Meignen 2000). The original researcher (Li 1993) had briefly reported the presence of MP blade techniques at Guanyindong, and we described these cores as blade cores in our previous paper as well. However, in this current study, these cores have been reclassified as 'volumetric exploitation' in consideration of the lack of exclusive analysis and insufficient evidence such as end-products and specific technical artifacts. Moreover, this terminology shift is intended to underscore the diverse concepts within core reduction systems rather than focusing on end-products or delving into the intricate cultural and geographical contexts associated with blade approaches (e.g., Bar-Yosef and Kuhn 1999; Hoggard 2017; Meignen and Bar-Yosef 2020; Wojtczak 2022; Zwyns 2012).

To confirm the Levallois reduction sequence, we used an empirical and quantitative approaches, in addition to Boëda's definition and morphology. This includes Lycett and Eren's method to compare the coefficients of variation (CV) of non-Levallois flakes and preferential Levallois flakes (Brantingham and Kuhn 2001; Lycett and Eren 2013). The Quina retouch was identified according to the definition of Quina debitage by Bourguignon and the interpretations of subsequent scholars (Hiscock et al. 2009).

Results

Raw materials

The raw materials of the assemblage are dominated by chert (77.3%) followed by limestone (21.7%) and basalt (0.9%). Other materials (such as sandstone and quartz) were only rarely used (0.4%) (Table 1). The majority of raw materials are accessible within 6 km of the site (Leng 2001; Li et al. 2009). Specifically, chert is available within about 2–6 km, while limestone and volcanic rocks (such as basalt and quartz) are all available from local mountains, river bed and exposed deposits. The dominant exploitation of chert for core reduction and tool manufacture suggests that the Guanyindong hominins intentionally selected chert as the raw material. Raw materials management is an important component of technological organization. Their exploitation and economics were often integrated with mobility strategies (Shott 1986). The distance between workable raw materials and site locations allows insights into land-use and range of hunter-gathers travels (Brantingham 2003; Geneste 1985; Kelly and Todd 1988; Kuhn 1989; Wallace and Shea 2006). The foraging range over the landscape, if assessed solely by the distance of raw material, was restricted within nearby sources (< 5 km) or relatively close localities (5–20 km) at Guanyindong.

Core reduction

There are about 248 cores found in the assemblage (see examples in Fig. 2), whose basic attributes are summarized in Table 2. The median maximum dimension (the greatest linear measurement of a specimen) of them is 72 mm. The median dimensions are 43.5 × 55 × 47 mm (L*W*Th). The median weight of cores is 149.5 g. Chert dominates the raw material of cores, with limited contribution of alternative raw materials (Fig. 4). Various geometries of cores were found, including irregular (80.5%), conic (9.8%), column (6.7%) and small amounts of wedged and circular (3%). In terms of the number of platforms, three types of cores can be identified (Fig. 3a): single platform (60.5%), double platform (27.2%) and multiple platform (11.7%). This indicates that 40% of the cores were rotated one or more times to find a new platform (or angle), after current platform and the original platform was no longer suitable for further striking. The majority (80%) of cores have 1–4 flake scars, and some (16%) have 5–7 scars. Only a small quantity (4%) have more than 7 scars (Fig. 3b). The distribution of length of the flake scars on cores is shown in Fig. 3c, these scars are generally between 20 and 40 mm. Most cores (78%) are covered with zero or a low percentage (< 25%) of cortex (Fig. 3d). The cortex locations are always on platforms and bottoms. The majority of platform types are plain (54%), followed by facetted platforms (18.2%) (Fig. 3e).

In terms of technological traits, most cores are polar/unifacial cores (61.6%), which means they are unifacially knapped whenever raw material morphologies and platform angles allow successful percussion. This is also known as 'migrating platform core reduction' or '*Système par Surface de débitage Alterné*' (SSDA) (Forestier 1993). The reduction of polar/unifacial cores may also involve several rotations as long as knappers find the ideal striking location on the blank. In contrast with polar/unifacial

Fig. 2 Photographs showing selected cores and flakes. (**a**-**b**, **d**) Single platform cores; (**c**, **e**) Double platform cores; (**f**) Discoid cores; (**g**) Flake with gull-wing platform; (**h**) core-on-flake; (**i**) Triangular flake; (**j**) Flake with gull-wing platform and a main triangular scar covers the dorsal surface; (**k**-**n**) Flakes with various shapes; (**o**) Crest flake; (**p**) Volumetric exploitation core

Table 2 Summary of mean, standard deviation (SD), coefficient of variation (CV) for basic core attributes

	Length (mm)	maximum dimension (mm)	medial width (mm)	distal width (mm)	thickness (mm)	distal thickness (mm)	mass (g)	scar number	cortex percentage (%)
mean	47.2	75.1	58.0	49.2	51.8	38.7	198.9	2.9	14.5
SD	20.2	21.6	21.2	21.5	29.6	17.1	166.8	2.0	19.4
CV	0.4	0.3	0.4	0.4	0.6	0.4	0.8	0.7	1.3

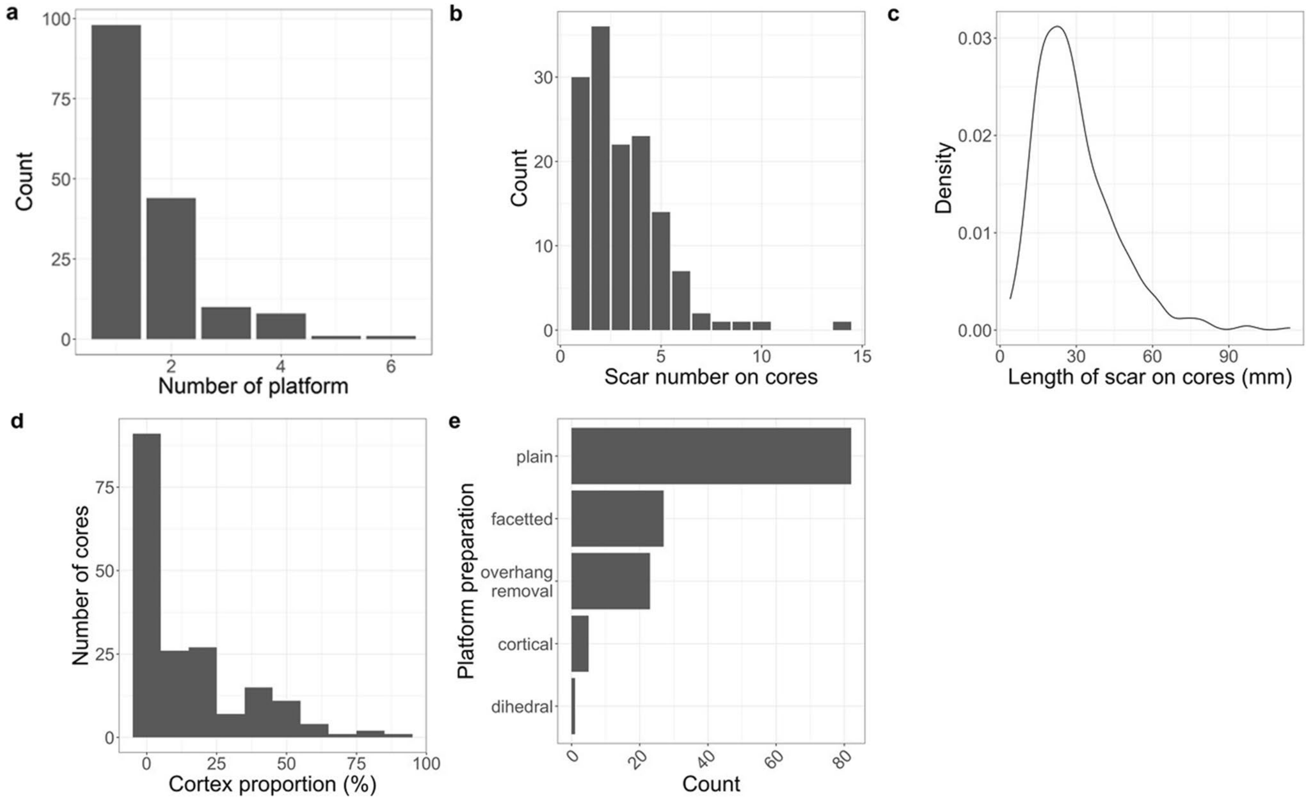


Fig. 3 Statistical results of cores. (**a**, **b**, **d**, **e**) Histograms showing the number of cores with different number of platforms, scar number, cortex proportion and platform types; (**c**) Density distribution of the scar length on cores

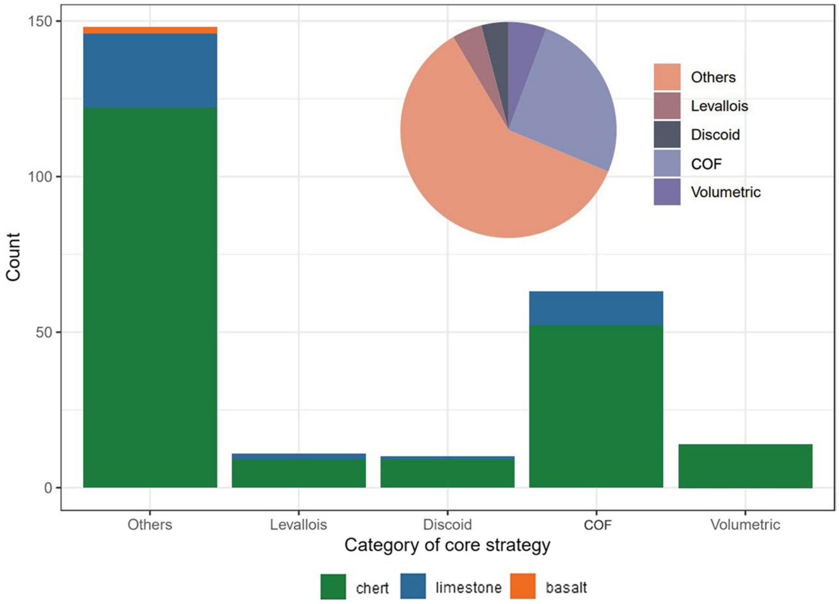
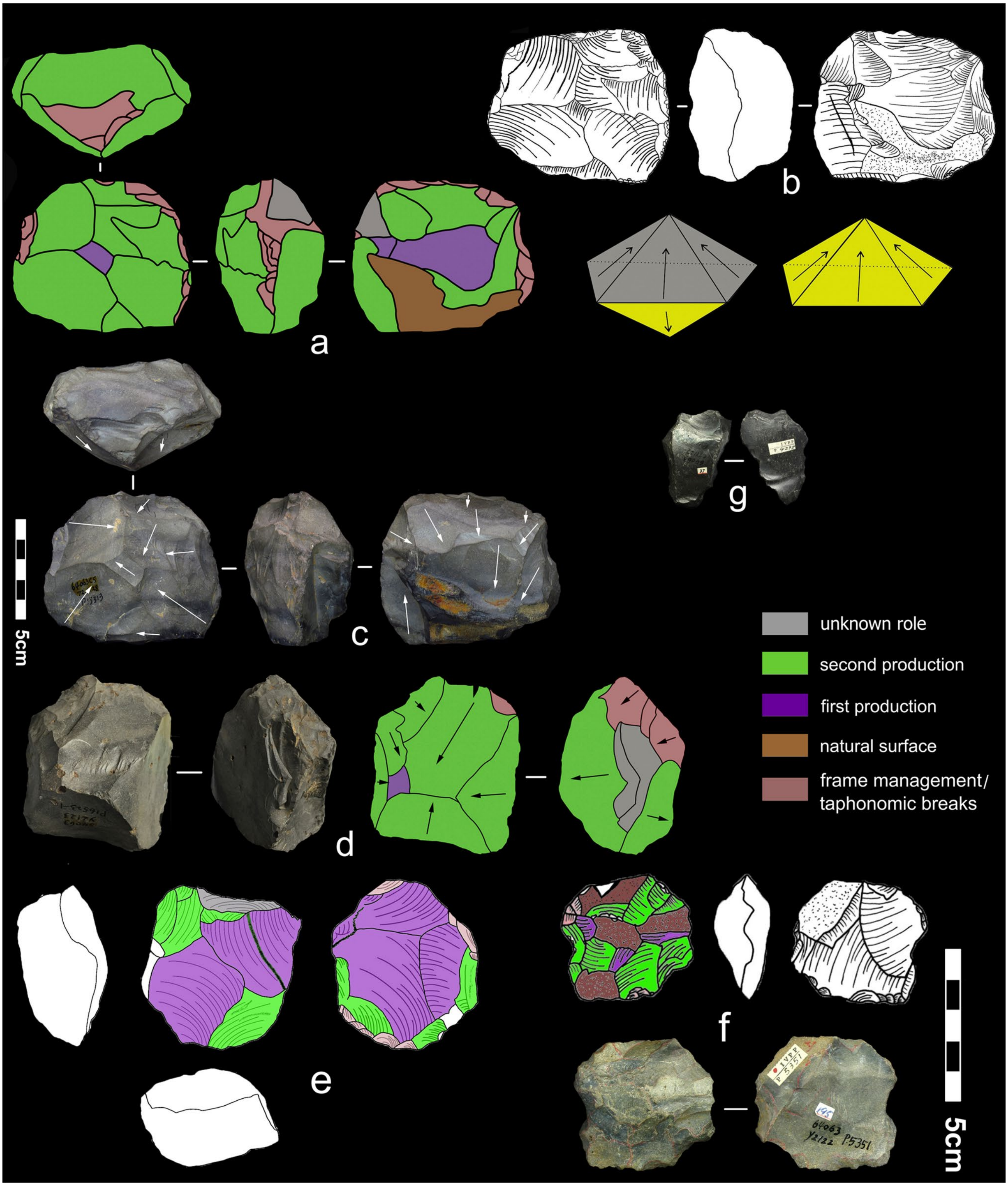


Fig. 4 Bar chart illustrating the composition of raw materials for each core strategy and pie chart showing the distribution proportions of individual core strategies within the core assemblage. The category "Others" encompasses polar/unifacial cores and a small quantity of other assortments. "COF" represents core-on-flake

cores, a number of cores exhibiting other schemes of reduction were found (Fig. 4). They are discoid cores ($n = 10$; 4%), core-on-flakes ($n = 62$; 25.4%), volumetric exploitation cores (n = 12; 5%), Levallois cores ($n = 11$; 4%), and a small number of others (i.e., bifacial core, hemispheric core). These core types also exhibit a higher level of standardization in geometric configurations compared to polar/unifacial cores. Cores exhibiting the highest



regularity are volumetric exploitation cores, which possess prismatic, wedged, or conic geometries up to 58.3%. Discoid cores (50%, conic) represent the second most regular core type, while Levallois cores exhibit the least regularity (less than 30%).

In order to investigate the complexity of the core reduction system in detail, each individual system is described below. However, as comprehensive discussions on Levallois cores have been presented elsewhere (Hu et al. 2019a,b, 2023a), only a concise summary is included here.

◂**Fig. 5** Discoid cores and flakes. (**a**-**c**) Scheme, sketch and photograph of a Discoid core, the white arrows show the directions of removals. The core is formed by two surfaces, with radioactive recurrent scars from two production phases left on each surface (one surface is complete peripheral exploitation and the other is partial peripheral exploitation). (**d**) Photograph and scheme of another Discoid core. The black arrows show the directions of the centripetal removals on the debitage surface. The other surface is minimally exploited. (**e**) Discoid core with two exchangeable surfaces; (**f**) Scheme, sketch and photograph of a Discoid core with single working surface. (**g**) Triangle flake with a main triangular scar covers the dorsal surface. Schematic model sketch shows two types of discoidal reduction patterns. Note that some photographs of stone artifacts are edited from the same original photographs with those in SI in Hu et al. (2019b), similarly hereinafter. The categorization of 'first production' and 'second production' is based on their chronological order of reduction sequence. "Frame management/taphonomic breaks" are the final removals typically found along the edges of the core platforms. These removals may serve as an alternative form of platform preparation or be results of post-depositional influences, similarly hereinafter

Levallois concept

The Levallois core reduction process was observed on 11 cores, 30 flakes and 4 retouched flakes. Blanks for core reduction are mostly chert nodules around 100 mm. The proportion of Levallois products within the entire assemblage is 1.99% (0.49% for cores and 1.5% for flake pieces). Although this percentage appears relatively low compared to Levallois Mousterian assemblages (e.g. Goder-Goldberger et al. 2012; Shea 2003), cross-site comparisons suggest that such a low proportion is not uncommon when considering early Middle Stone Age assemblages such as the Kapthurin Formation and Omo (Shea 2008; Tryon et al. 2005). Removal patterns on the upper surfaces of cores indicate the utilization of both preferential and recurrent approaches to generate oriented products. Convexity maintenance was achieved through centripetal, bidirectional, unidirectional and convergent methods. Amongst, the dominant technical combination employed was centripetal preferential ($n=6$, 55%). Based on these observations, the Levallois production process at Guanyindong commonly involves selecting chert nodules of a specific size and preparing a striking platform for subsequent convexity preparation, which is achieved through centripetal removals, occasionally utilizing bidirectional, unidirectional, or convergent patterns. Finally, a determined flake was detached parallel or sub-parallel to the intersection plane of the lower and upper surfaces.

It is noteworthy that the preparations for striking platform and convexity maintenance are comparatively less complex when compared to both Levallois Mousterian industries and Africa Levallois assemblages. However, the disparity appears to primarily be at a quantitative level rather than in terms of conceptual divergence, according to current evidence. The exact origins of such core technology, traced back to 180 – 80 ka at Guanyindong, remain elusive. Population migrations and cultural convergence are plausible but require further substantiation through additional archaeological evidence. Investigating the null hypothesis of 'opportunistic' and 'accidental' occurrences necessitates simulated experiments and a more quantitative approach (Eren and Lycett 2012, 2016; Lycett and von Cramon-Taubadel 2015).

Discoid Production

Discoid debitage has been found in many sites and shows substantial variability (Pasty 2000). The use of the Discoid method at Guanyindong is indicated by ten Discoid cores (see examples in Figs. 2 and 5) and diversified products that are potentially pertinent to this system, such as triangles, and short, thick flakes as well as pseudo-Levallois points.

Two distinct types of discoidal cores were identified at Guanyindong. One conforms to the definition according to Boëda (1995), featuring two exchangeable surfaces that can serve as both flaking or striking surface (Fig. 5a-c). The other discoidal exploitation is characterized by one surface remaining flat as a dedicated striking platform, while the other surface exhibits centripetal scars extending to the distal end serving as a flaking surface (Figs. 2f and 5d-f). Both types of discoidal cores attest the presence of discoid production at Guanyindong, with the later type more common. Core sizes are moderate, around 73 mm long (median max dimension) with median mass about 129 g. According to the major scars remaining on the working surface, cores usually yield 4–6 successive flakes. More than half of them have partial cortex (the cortex covers mostly 10%, but 50% on some extreme specimens) remaining on the platforms or distal places, probably as a result of local or early stage of manufacture.

A variety of end-products/by-products of Discoid production are found at Guanyindong. They are mainly thick débordant flakes, triangular and quadrangular flakes (see examples in Figs. 2-i, g and n and 5g). Most of them were retouched into tools. A small number of pseudo-Levallois points (Fig. 6), that can be produced from both Levallois methods and Discoid production, serve as indirect indicators of Discoid production at Guanyindong.

Core-on-flakes

Core-on-flakes (related terms include core-on-flake, Cores on Flakes, Cores-On-Flakes (COF), flakes-cores, ramification etc.) is a lithic production strategy that widely observed from Lower to Middle Palaeolithic assemblages (e.g. Goren-Inbar 1988; Hiscock 2007; Hovers 2007; Mathias 2016; Mathias and Bourguignon 2020; McPherron 2007; Owen 1938; Rossoni-Notter et al. 2016; Solecki 1970). At Guanyindong, core-on-flake strategies are evident on 83

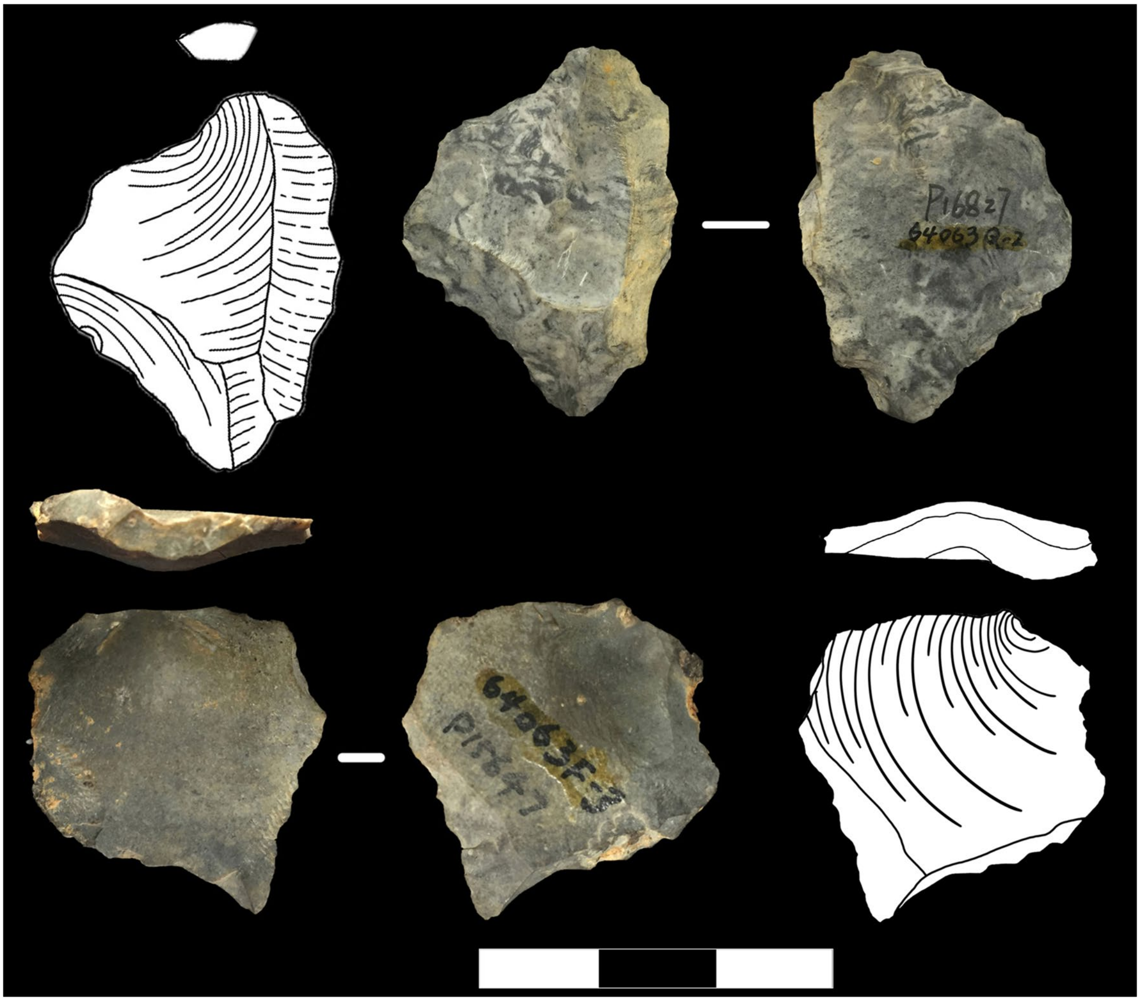


Fig. 6 Enlarged photographs and sketches of Pseudo-Levallois points

stone artifacts, including both cores and flakes (Figs. 2h and 7). Here, they are defined by the recycling use of flakes into production of secondary debitages, especially on ventral surfaces. In Fig. 7-a, c, and d, cores show truncations, on one or more margins, that was used as platforms for the removal of one or more small flakes from the flaking surface. Such patterns are known as truncated-facetted pieces or Nahr Ibrahim Technique (Faivre 2008; Goren-Inbar 1988; Hovers 2007; Schroeder 2007; Shalagina et al. 2015). This strategy is often regarded as a response to lithic raw material scarcity and indicative of highly mobile forager groups (Wallace and Shea 2006), and also suggests a predetermination concept, since this strategy requires multi-stage production, indicating advance planning (Brantingham et al. 2000).

The likely functions of core-on-flakes are disputed. Some believe they are a type of prepared core (Brantingham et al. 2000), while others primarily regard them as tools (Shalagina et al. 2015) or “specific oriented products” (Dibble 1984), or thinning for hafting (Schroeder 2007). In the case of Guanyindong, although we cannot exclude the possible of tool usage, their primary function as cores is more plausible. First, the median maximum dimension of retouched tools and complete flakes is 54.1 mm and 61 mm respectively. Core-on-flakes have size (median max dimension is 73.5 mm) larger than both of them, and closer to the cores (75 mm). Seemingly, larger flakes are intentionally selected for this production strategy. Second, we set 15 mm as the threshold value for secondary removals. As indicated by the low Index of Invasiveness values (see Sect. 3.4), most of the tools were retouched marginally with retouch scars less than 10 mm. The value of 15 mm utmost avoided possible mixture with retouching scars. Third, although core-on-flakes can be knapped from both the ventral and dorsal sides, most removals in this category from the Guanyindong assemblage are ventral face removals, which foundationally avoid the confusion with tools that are dominated by retouch on dorsal surfaces.

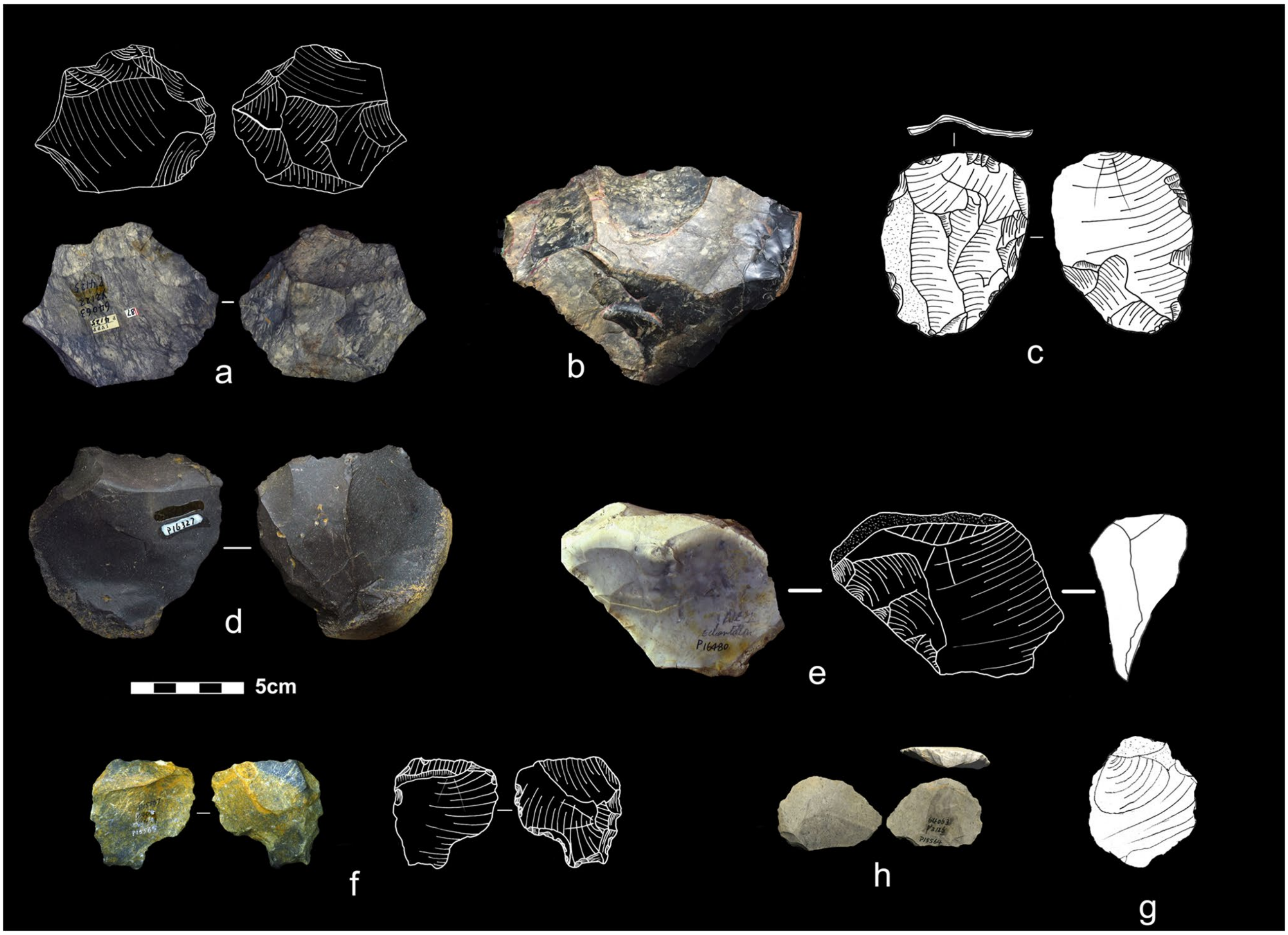


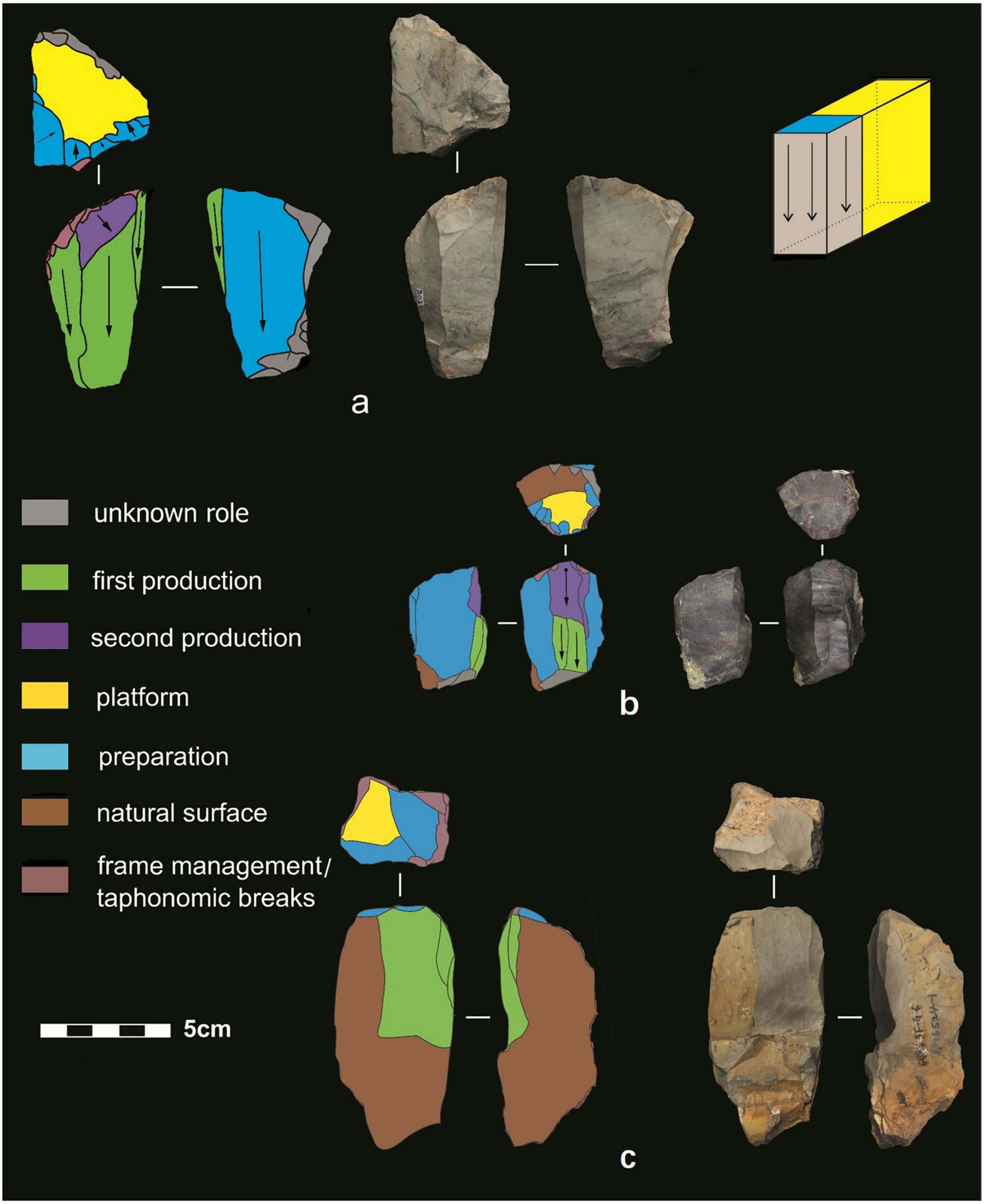
Fig. 7 Core-on-flakes and Kombewa flakes. (**a**-**e**, **g**) Cores with flake scars left on the ventral side of the origin flake; (**f**, **h**) Kombewa flakes consist of two ventral surfaces

The presence of Kombewa flakes ($n = 21$, Fig. 7f, h, median maximum dimension = 69 mm) at Guanyindong provides another important piece of evidence supporting the core-on-flake strategy. Kombewa production is well known in Africa, and has also been found in many lithic industries across Eurasia (see Boëda 2018; J. Wang 1994). It is found in Acheulean assemblages from Africa and Europe before the development of Levallois strategies (Inizan 1999). At Guanyindong, core-on-flake production was utilized to produce relatively small flakes with sharp edges.

Volumetric exploitation

Cores presenting volumetric exploitation appeared in small amounts ($n = 12$, see examples in Figs. 2p and 8). They were manufactured on various blanks such as chunks, nodular and flakes. The sizes of these cores are consistently smaller (the median max dimension of is 52.4 mm; the median length is 35 mm) than most cores, with no cores found larger than 100 mm. Most cores do not have cortex and the median number of scars is four. Almost half of their striking platforms were parsimoniously prepared. However, confined preparations are clearly demonstrated through successive small removals on the striking area, leaving the remainder of the surface nearly untouched (cortical or minimally prepared, Fig. 8 blue marker). Compared with other types of cores, most volumetric exploitation cores have little or no cortex. The morphologies of cores are relatively more regular. This regularity probably started during the selection process of blanks, which was intentionally focused on columnar nodules or chunks with one flat surface that potentially severed as striking platform afterwards. Except for utilizing the natural narrow face on the lateral of a core's perimeter, anthropogenic efforts are spent on some cores' volumes by thinning the working surface through detachment of rear lateral removals (Carmignani et al. 2017). That said, most cores are only minimally prepared, and are not thoroughly shaped out before starting the production.

This production system deliberately reduced the narrow surface of the long-axis, which mechanically caused



increasing difficulty in successfully removing flakes. We infer this risky exploitation was driven by the demand for narrow/elongated flakes. A small number of corresponding products were found (narrow and elongated flakes, $n=11$). Overall, apart from the overlap between 40 and 70 mm, these flakes exhibit a statistically longer length compared to

◀**Fig. 8** Volumetric exploitation cores. (**a**) Scheme and photograph of a volumetric exploitation core, from which three oriented products are detached. The platform of striking area is prepared and the lateral part of the volume is removed in order to preparing the flaking surface. (**b**) Scheme, photograph and sketch of another volumetric exploitation core, from which successive end-products were achieved. Platform of the end products are prepared. Lateral parts of flaking surface are removed in order to centralize the flaking surface. (**c**) Scheme and photograph of another volumetric exploitation core. The black arrows with black circle show the directions and impacts of removals. The volume reduction has two phases. The first reduction was successful, yielding two oriented products, while the subsequent reduction failed but took away the proximal of previous removals. Striking platform and lateral of flaking surface is somewhat prepared. Schematic model sketch shows the reduction patterns of volumetric exploitation cores

cores (t (13.0) = 2.40, $p = 0.032$). This difference in size indicates that cores may have reached a later stage and become exhausted during the knapping process, while these elongated flakes were produced in earlier stages.

The creation and transformation of raw material blanks into volumetric exploitations reveals core configuration utilization strategies. Although it resembles MP laminar and non-Levallois blade reduction (Delagnes 2000; Meignen 1994; Révillion 1995) in a way, adequate evidence to support the link in this assemblage is lacking, because of the near absence of *chaines opératoires* which designate intentional and systematic blade knapping methods. Similar functional tests applied to blade production (e.g., Hoggard 2017) would undoubtedly be beneficial to understand this approach at Guanyindong. Nonetheless, it is important to note that this type of core management is not likely opportunistic, as there is a notable small tendency in core dimensions when compared to other core types, suggesting a systematic pattern rather than random behaviors. Furthermore, although it can be difficult to unquestionably distinguish this exploitation method from endscraper retouching, on some individual pieces (see Sect. 3.4), the presence of both in this assemblage indicates a skill in controlling parallel removals.

Flakes

Among the 1,138 flake pieces studied (see Fig. 2 for selected specimens), there are 189 complete flakes, 214 retouched flakes, 6 flake breaks and 729 retouched flake breaks. The predominant raw material for flakes is chert (77.7%), followed by limestone (21%) and a minor proportion of other rocks (1.3%). The flaking technique is mainly percussion with hard hammer.

Table 3 summarizes basic flake mean attributes, where specific standard deviations and coefficients of variation are available. The median dimensions of complete flakes are 48 × 49 × 16 mm (L*W*Th); this is larger than that of scars remained on the cores, suggesting that many of the flakes were obtained outside of the cave, or core volumes were exhausted before abandonment. The majority of flakes have masses from 10 to 100 g (Fig. 9a) and maximum dimensions from 20 to 80 mm (Fig. 9). The median maximum dimension of flakes pieces is ~ 60 mm. A large number of flakes have a ratio less than three, signifying these flakes are relatively thick. Both the thickness and width at 50% of maximum dimension are systematically and slightly larger than those at the other parts. This means the thickest and widest part of flakes are in the middle, suggesting a consistent inclination over core peripheral convexity. More than 80% of the flakes (including retouched flakes) have no cortex (Fig. 9). The cortex proportion of those flakes is mainly restricted from 5 to 10%. It suggests that most of flakes were introduced into the assemblage at later stages of reduction, and hominins took secondary products into the cave after they initially knapped blanks outside.

There are 396 artifacts that have distinguishable platforms, which can be divided into cortical ($n = 36$; 9.1%), plain ($n = 212$; 53.5%), faceted ($n = 43$; 10.9%), dihedral ($n = 45$; 11.4%) and punctiform ($n = 20$; 5.1%). Although the plain and cortical platforms make up the largest proportion, flakes with prepared platforms are frequently shown, confirming complicated skills other than simply unifacial removal. Flakes with faceted platforms are systematically larger than other platform types (Fig. 9h), indicating that hominins prepared flake platforms as part of a strategy to produce larger flakes. The mean dorsal scar number is three (Table 3) and flakes with three dorsal scars also account for the largest proportion (Fig. 9d). Flakes with more than five scars are rare. However, they are generally larger than those flakes with fewer scars (Fig. 9).

The median dimension of flake platforms is 31 × 12 mm (W * Th, Fig. 10a). Flake platform shapes include triangular ($n = 136$; 44%), quadrangular ($n = 87$; 28%), fusiform ($n = 46$; 15%), and gull–wing ($n = 31$; 10%, cross sections resemble "gull's wing", (Faulkner 1972), see example in Fig. 2g, j) and with a small number of trapezoids, rectangle, and irregular (Fig. 10b). To test the possible relationships between platform shapes and flake dimension, we compared the maximum dimension as well as thickness at 50% of maximum dimension for different platform shapes (Fig. 10c and d). We found that flakes with gull–wing and fusiform platforms are slightly thinner (median thickness at 50% of maximum dimension is 11.8 mm), and those with triangular platforms are the thickest (median thickness at 50% of maximum dimension is 18.4 mm). Similar patterns are observed for the maximum dimension, i.e., triangular platforms are more frequently found on larger flakes (median maximum dimension: 63.4 mm compared to 55 mm for the rest; t (151.0) = 2.40, $p = 0.018$).

The directions of dorsal scars from 356 flakes were recorded. We divided the directions into 8 sections (Fig. 11a). Except for 85 scars that could not be oriented,

Table 3 Summary of mean, standard deviation (SD), coefficient of variation (CV) for basic flake attributes

	length (mm)	maximum dimension (mm)	oriented width (mm)	width at 25% maximum dimension (mm)	width at 50% maximum dimension (mm)	width at 75% maximum dimension (mm)	oriented thickness (mm)	thickness at 25% maximum dimension (mm)	thickness at 50% maximum dimension (mm)	thickness at 75% maximum dimension (mm)	mass (g)	platform width	platform thickness (mm)	scar number	cortex percentage (%)
mean	49.4	62.5	50.3	36.3	41.9	35.2	17.6	16.1	16.6	13.7	68.2	32.8	13.7	2.9	9.4
SD	19.2	22.5	19.2	14.1	15.3	14.8	8.1	7.6	7.8	6.8	81.7	16.8	7.8	1.6	15.1
CV	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	1.2	0.5	0.6	0.6	1.6

the number of dorsal scars in each direction were recorded. Among them, 221 flakes have dorsal scars that have the same directions of the flake's percussion axis. The other major directions are from directions 2, 3 and 8 (marked in the gray semi-circle) suggesting that most of the previous flakes on original cores have similar directions of the final detachment. In other words, unipolar or unipolar convergent direction were the first choices when knapping a core.

Fourteen elongated pieces, including 11 elongated flakes and 3 crest flakes are found. The median maximum dimension of them is about 74 mm, slightly larger than volumetric exploitation cores and their platforms are mostly unprepared.

Coefficients of Levallois flake variation

Levallois debitage systems are often claimed to be optimal (Brantingham and Kuhn 2001; Eren and Lycett 2012; Lycett and Eren 2013; Picin and Vaquero 2016) in terms of raw material economics and flake utility since they increase the raw material's efficiency and the length of cutting edge that can be created from a given blank. Thus, Levallois flakes often exhibit a greater standardization in their attributes compared with the 'non-preferred' flakes. To test this, we examined metric standardization of these two groups of flakes (Table 4). The CV of several attributes on Levallois and complete flakes (including retouched complete flakes whose shape were not seriously varied by retouching) are compared. We found that the CV values of Levallois flakes are substantially smaller than those of complete flakes (Mann-Whitney $W=61$; $p=0.033$), consistent with previous finds that Levallois flakes are more standardized than other complete flakes (Lycett and Eren 2013). We found that mass and metric dimensions are similar between Levallois and non-Levallois, but Levallois flakes are thinner than non-Levallois flakes (Fig. 12a-c). We infer that the Levallois strategy was employed at Guanyindong to reliably produce thinner flakes. Although the results of our comparison shows that Levallois flakes are statistically distinctive, concluding definitively whether they were 'preferred' would benefit from further analysis, such as use-wear and refitting analysis.

Retouched pieces

A total of 999 retouched pieces were found in the assemblage, accounting for 45% of lithic assemblage (see examples from Fig. 13). The selection of blank for tool production demonstrates an obvious favor of flake or flake breaks (95%). Most retouched pieces are made on flakes breaks (~ 70%) and complete flakes (~ 20%), a small number of them are made on either chunks or pebbles. The median maximum dimension is 54.1 mm. The max dimensions and masses of retouched flake are generally smaller than unretouched flakes, suggesting that they probably come from

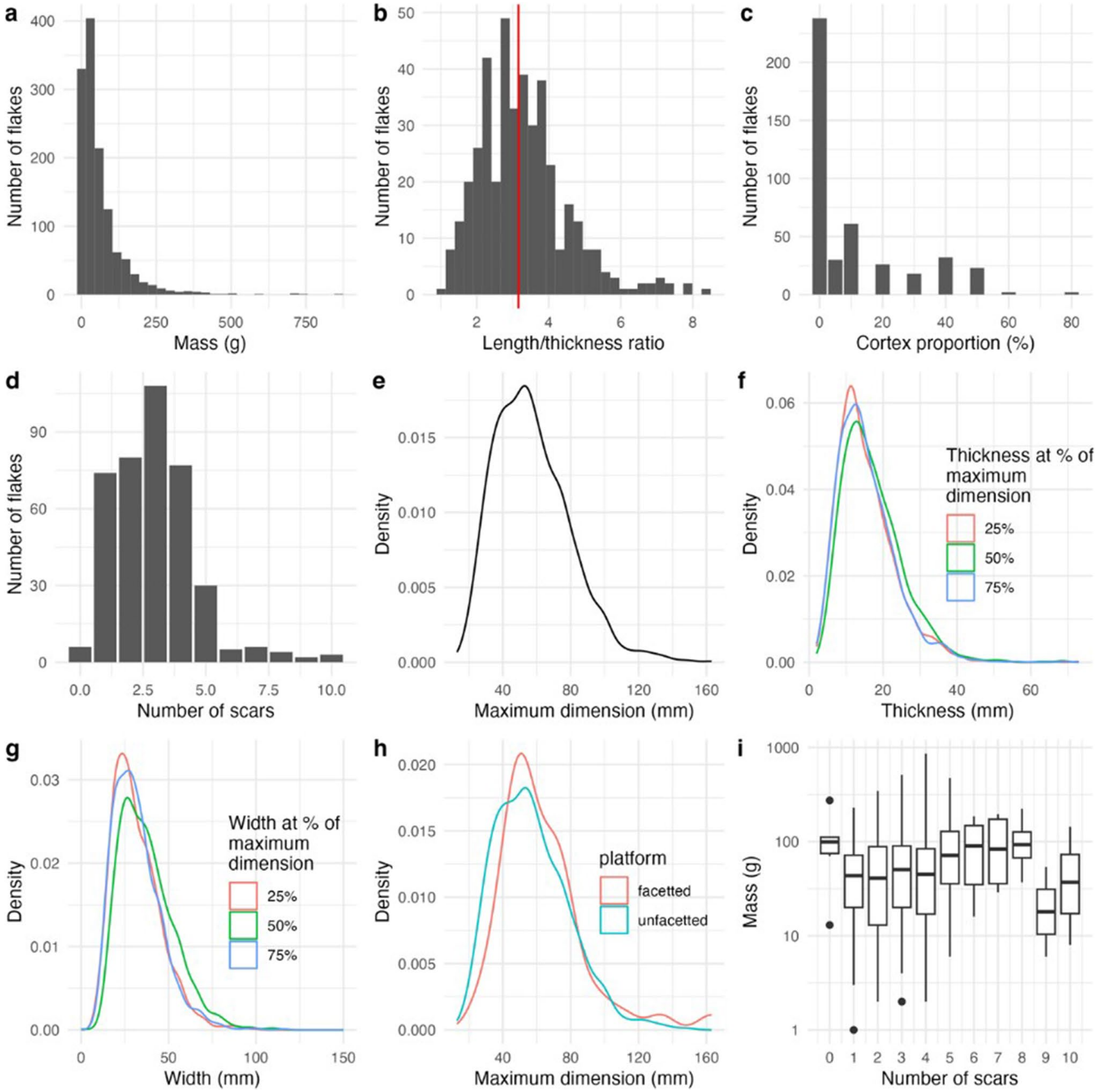


Fig. 9 Statistical results for flakes. (**a**-**d**) The counts of flakes for different mass, different length/thickness ratios (red line shows the median value), cortex proportion and number of dorsal scars. (**e**-**g**) Density distribution of flakes for different maximum dimension, thickness, and width (two outliers are not shown). (h) Comparison of density distributions of flakes with and without faceted platforms. (**i**) Box plots showing the mass difference between flakes by scar number

the same reduction sequence (Fig. 14a). Side scrapers and denticulates dominate retouched pieces (65%), followed by borers (6%) and other types (see Table 1).

The locations and shapes of retouch and the properties of the retouching scars provide further insight into tool manufacturing and management. Among the 1,559 retouched edges that recorded (Fig. 14b), straight edges constitute the largest proportion ($n = 575$, Fig. 15a) followed by convex ($n = 395$, Figs. 15c and 16a) and concave edges ($n = 248$, Figs. 15b and 16b). We calculated the edge angles on eight sections of a tool using the method provided by Eren and Lycett (2016, see Fig. 11b). In Fig. 14c we see that the angles of section 1 to 8 are similar, mainly between 50° and 80°. The median angle of all edges is 67°. This suggests that

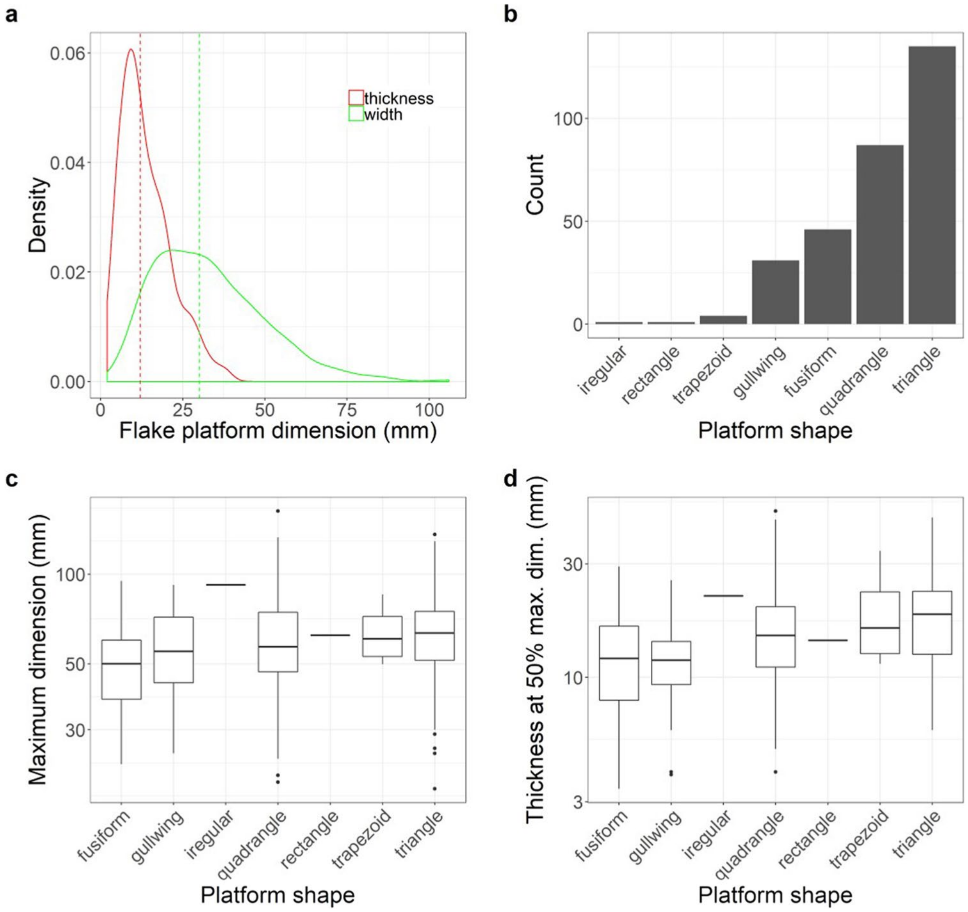


Fig. 10 Statistical results for flake platforms. (**a**) Density distribution of flakes' platform thickness and width (dotted lines show mean values). (**b**) Number of flakes with different platform shapes. (**c**) Box plots showing the maximum dimension of flakes with different platform shapes. (**d**) Box plots showing thickness at 50% maximum dimension of flakes with different platform shapes

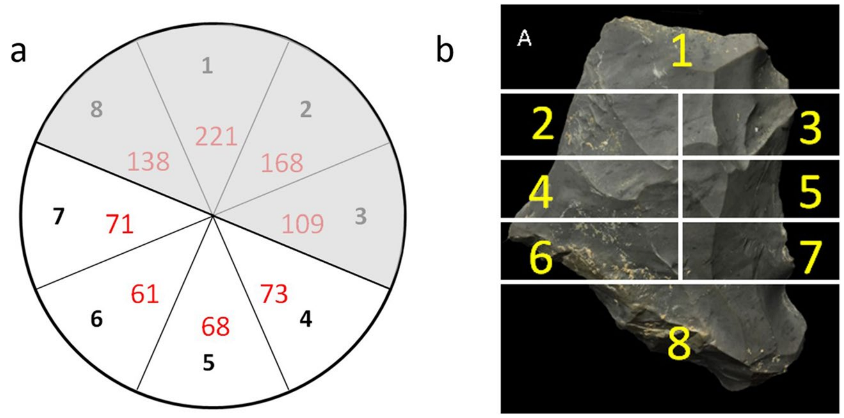


Fig. 11 Dorsal scar directions and zone of a tool. (**a**) Sketch showing the dorsal scar directions of flakes. The numbers in black are directions showing the scar directions (e.g., '1' from platform; '3' from right lateral; '5' from distal; '7' from left lateral). The numbers in red are the counts of dorsal scars that come from this direction. The gray area marks the most frequent dorsal scar directions. (**b**) Division of 8 sections on a tool

the edge angles of the entire blank were indiscriminately retouched, and relatively steeply (see example from Fig. 17). More than half of all retouched pieces were retouched on two or more edges (Fig. 18). Those data suggest extensive exploitation of blanks, probably resulting from repeated episodes of recycling and resharpening.

We used two indices, the index of invasiveness and the Geometric Index of Unifacial Reduction (GIUR) (Hiscock and Clarkson 2005; Hiscock and Tabrett 2010; Kuhn 1990) to estimate the intensity of retouch. Most specimens were extensively retouched, i.e., more than 60% have a GIUR value greater than 0.5. In order to investigate whether smaller pieces were more intensively retouched than larger pieces, we divided the flakes into clusters of sizes based on a dynamic programming algorithm for optimal one-dimensional k-means clustering, which selects optimal number of clusters of flake sizes based on the Gaussian mixture model using the Bayesian information criterion (BIC). We choose this approach because our exploratory data analysis indicated non-linear responses between size

Table 4 Results of descriptive statistics for Levallois and non-levallois flakes. 'PLF' stands for preferential Levallois flake; 'CF' stands for complete flake

	Mean (mm)		SD		CV (%)		
	PLF	CF	PLF	CF	PLF	CF	Difference
Length	47.43	49.12	18.42	19.93	38.83	40.57	-1.74
Max dimension	55.96	62.73	20.25	24.47	36.18	39.00	-2.82
Oriented width	46.90	50.29	17.91	21.02	38.18	41.79	-3.61
Width at 25% max	32.40	36.06	12.40	14.59	38.27	40.47	-2.20
Width at 50% max	37.13	41.66	13.37	16.74	35.99	40.18	-4.18
Width at 75% max	30.60	34.96	12.49	15.88	40.82	45.42	-4.60
Oriented thickness	12.16	17.88	4.45	9.02	36.64	50.46	-13.82
Thickness at 25% max	11.05	16.10	4.44	8.14	40.20	50.55	-10.35
Thickness at 50% max	11.95	17.07	4.78	8.68	40.01	50.87	-10.86
Thickness at 75% max	10.04	14.24	4.29	7.68	42.74	53.93	-11.19
Platform width	31.69	33.46	16.38	18.28	51.68	54.64	-2.95
Platform thickness	10.98	13.30	4.66	8.07	42.46	60.67	-18.21

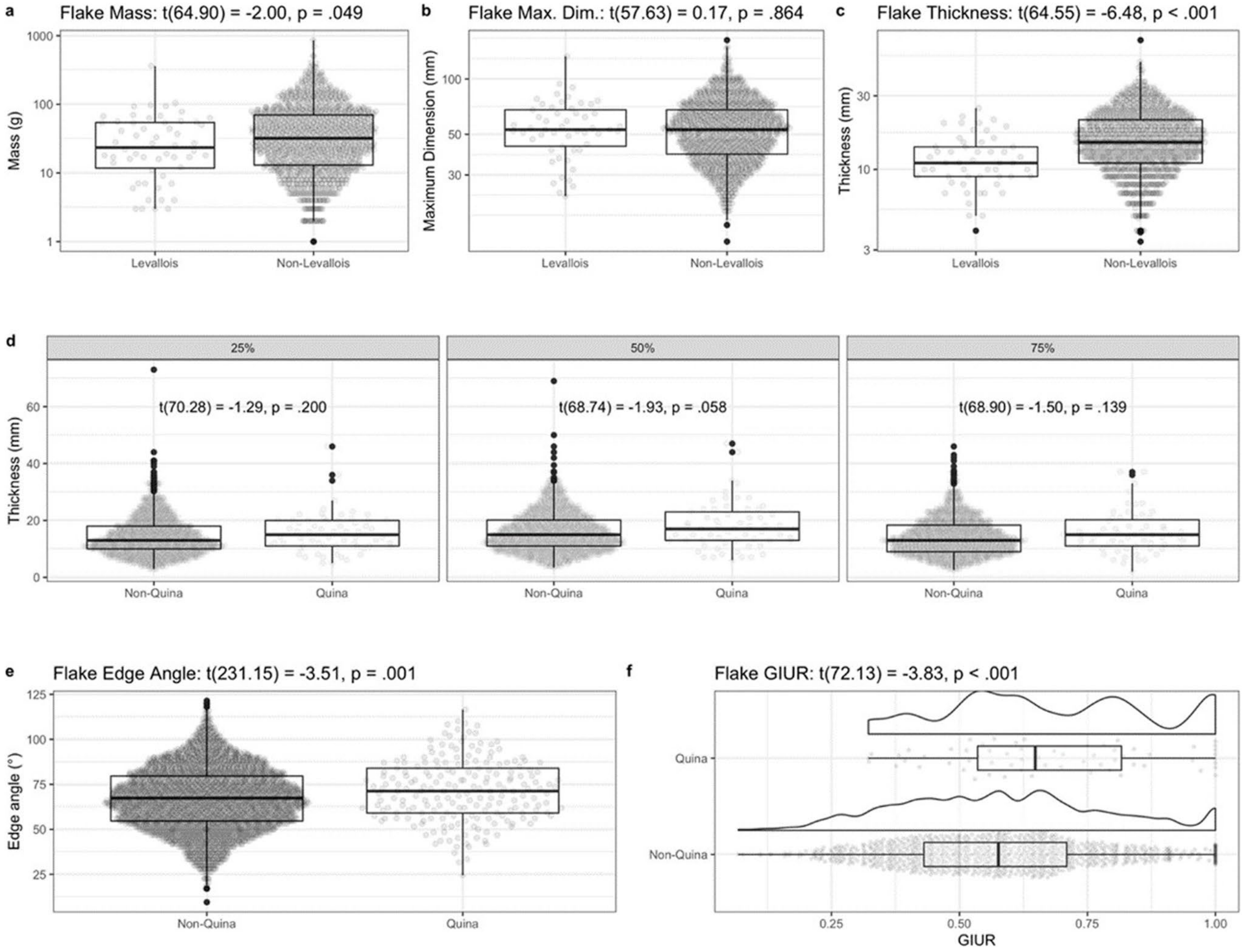


Fig. 12 Comparison of Levallois flakes vs. non-Levallois flakes and Quina tools vs. non-Quina tools. (**a** – **c**) Boxplots showing comparison between Levallois flakes and non-Levallois flakes on mass, maximum dimension and thickness at 50% of maximum dimension. (**d**) Boxplots showing comparison of thickness distributions between Quina and non-Quina tools at different locations on the flake (25%, 50% and 75% at maximum dimension). (**e**) Boxplots of edge angles between Quina and non-Quina tools. (**f**) Boxplots of GIUR of Quina and non-Quina tools, also showing a density line to reveal the details of the distribution of GIUR values. The output of Student's t-tests for differences in means are summarised in or on each plot panel

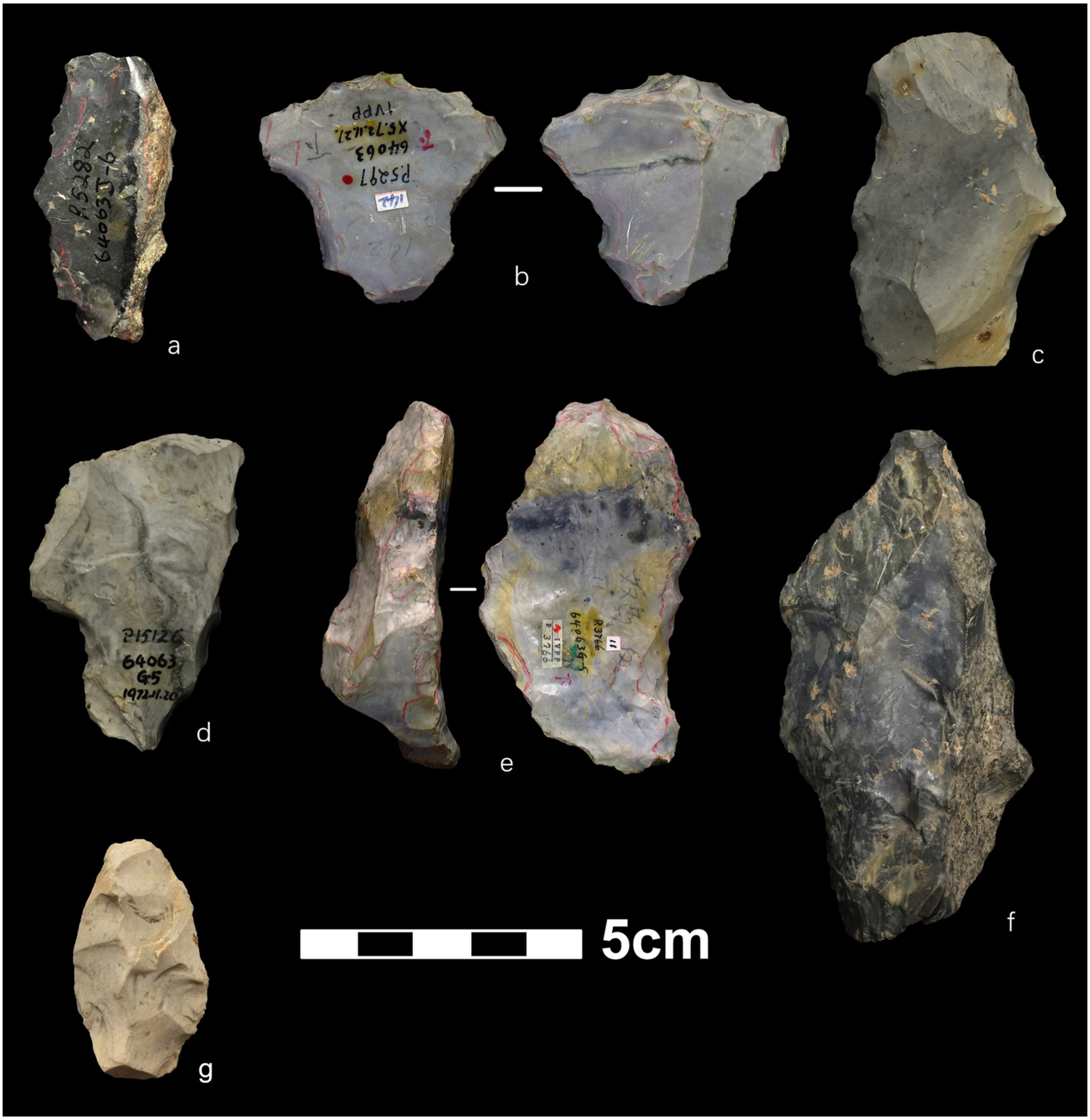


Fig. 13 Selected retouched pieces. (**a**, **f**) Natural backed knives; (**b**) Transverse scraper; (**c**, **e**) Scrapers with more than one working edges; (**g**) Scrapers that retouched holistically; (**d**) Notch

and key lithic attributes, making simple linear regression inappropriate for representing these relationships. In this case, the best model for our data indicated by the BIC values was five clusters. Figure 14d and e show the GIUR and index of invasiveness distributions according to different size groups. It shows that the smaller tools tend to have higher GIUR values (Fig. 14d). This is consistent with our prediction that small artefact sizes are a result of more extensive retouch and reuse. Index of invasiveness values are generally low for flakes (Fig. 14e). This is expected since the edges of most artefacts are too steep to allow the retouching scar to extend beyond half the depth of the zone. Over half of tools have more than one retouched edge (Fig. 14f; the edges are separated by an unretouched gap between each single retouch section). And as the number increased, the number of edges that have more than one

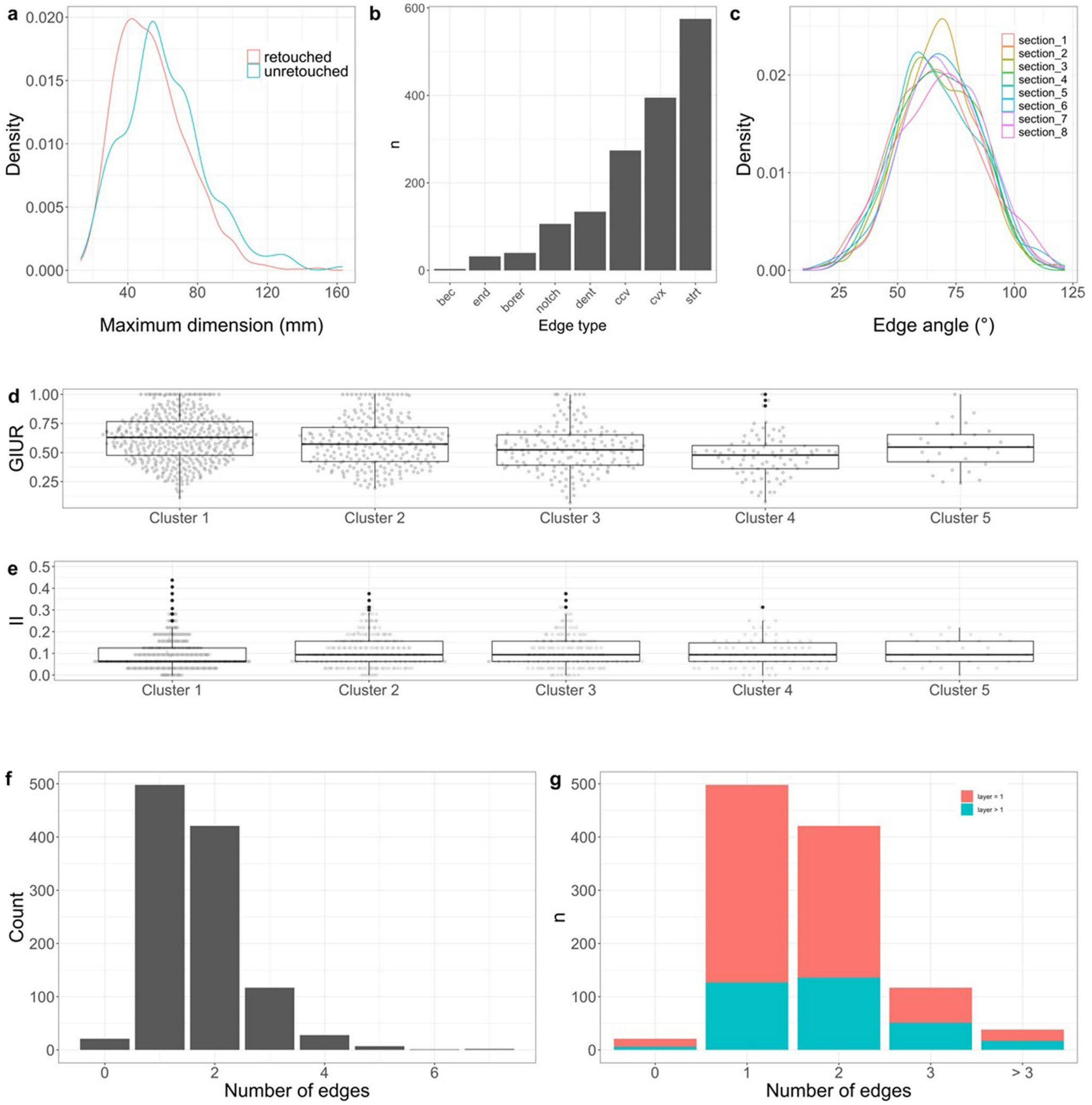


Fig. 14 Statistical results for tools. (**a**) Comparison of the density distribution of the maximum dimension between retouched and unretouched flakes. (**b**) Histogram showing the counts of tools for different edge types (dent: denticulate; ccv: concave; cvx: convex; strt: straight). (**c**) Comparison of edge angles among different sections. (**d**) Comparison of distribution of GIUR among 5 cluster groups of flakes with different masses. (**e**) Invasiveness Index (II) for the 5 cluster groups of flakes. (**f**) Histogram showing the counts of tools of different number of edges. (**g**) The counts of tools that have one and more than one retouching layers for tool with different edge number (1,2,3 and > 3)

retouched layer increases (Fig. 14g). They suggest that the tools were heavily recycled and the Guanyindong knappers were not only inclined to resharpen the edges with secondary retouch at the same location, but also attempted to create new edges when reusing their tools.

For notched ($n = 79$) pieces (see example in Fig. 13), the median depth and length is 3.7 and 11.6 mm. Most notches are Clactonian notches ($n = 51$, 65%). Ordinary notches only account for 32% ($n = 28$). The location of retouching is mainly on one longer geometric side of the piece.

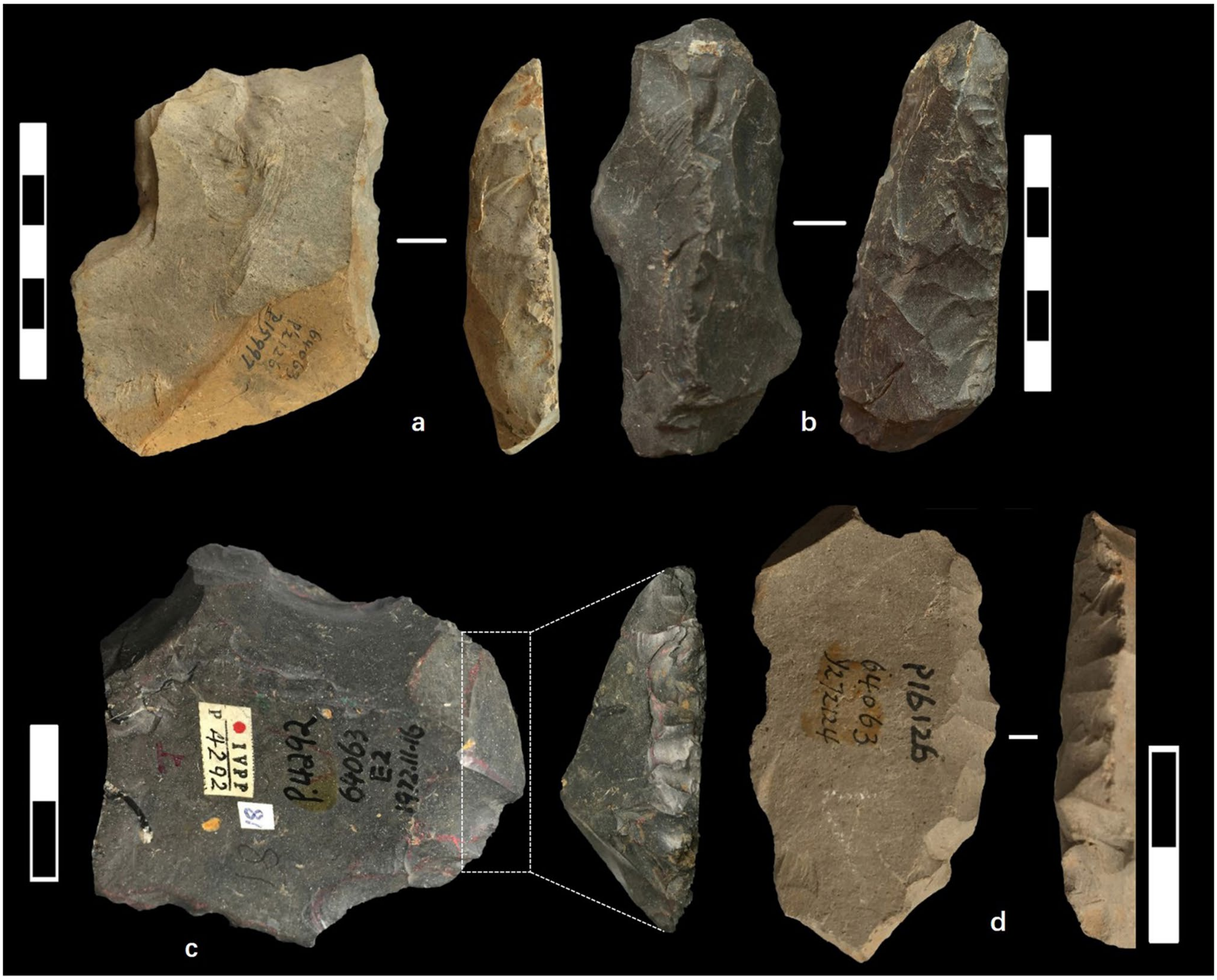


Fig. 15 Selected scrapers and denticulate. (**a**) Scraper with stright edge; (**b**) Scraper with concave edge; (**c**) Scraper with convex edge; (**d**) Denticulate with convex edge

Tools with regular forms

Despite that most retouched tools were modified with a great variety, a collection of elaborated retouches ($n = 58$) with regularity are present. Although they are not the dominant components, their appearance indicates a duality of elaborated and expedient modification strategies. Those tools primarily include elongated-pointed *pieces*, tanged points, endscrapers, miscellaneous denticulates, and borers.

Elongated-pointed pieces are tools exclusively retouched on elongated flakes on both lateral sides, forming a triangle and pointed morphology. Some pieces are thin and flat (Fig. 19a, b), while others are relatively thick (Fig. 19c, d). Instead of smooth edges, dentated lateral edges are more common. Regarding the existence of even scraper edges, we suggest that the commonness of dentated edges is not due to retouching capacity, but rather a functional choice. Some of this tool types represent modifications on butts, which suggest evidence of hafting (Fig. 19a, b). Except the case of the elongated-pointed pieces, some points/awls also show extensive and elaborated retouch on the opposite area against pointed tip (Fig. 20a, b) forming a distinctive tanged shape. Such patterns is speculated to be for hafting, however, their function needs to be examined with further microwear analysis. Other pieces with pointed shapes that resulted from adjustments on lateral edges in combined with tanged, but less elaborate, 'haft' working butts, were assigned to this typology as well, in terms of production organization (Fig. 20c, d).

We found 36 endscrapers (Fig. 21). They are classified according to parallel or sub-parallel retouching scars that created a steep and rounded working edge. Although the edges are not necessarily on the distal end of a flake, the retouched end is always narrowed, differentiating it from

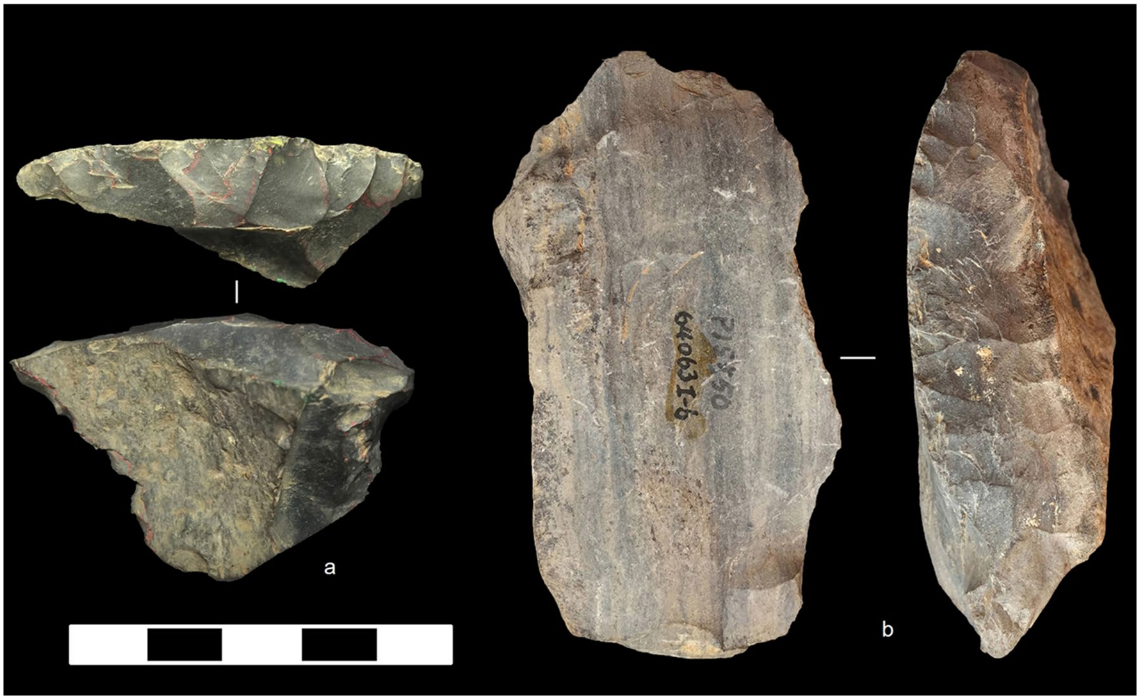
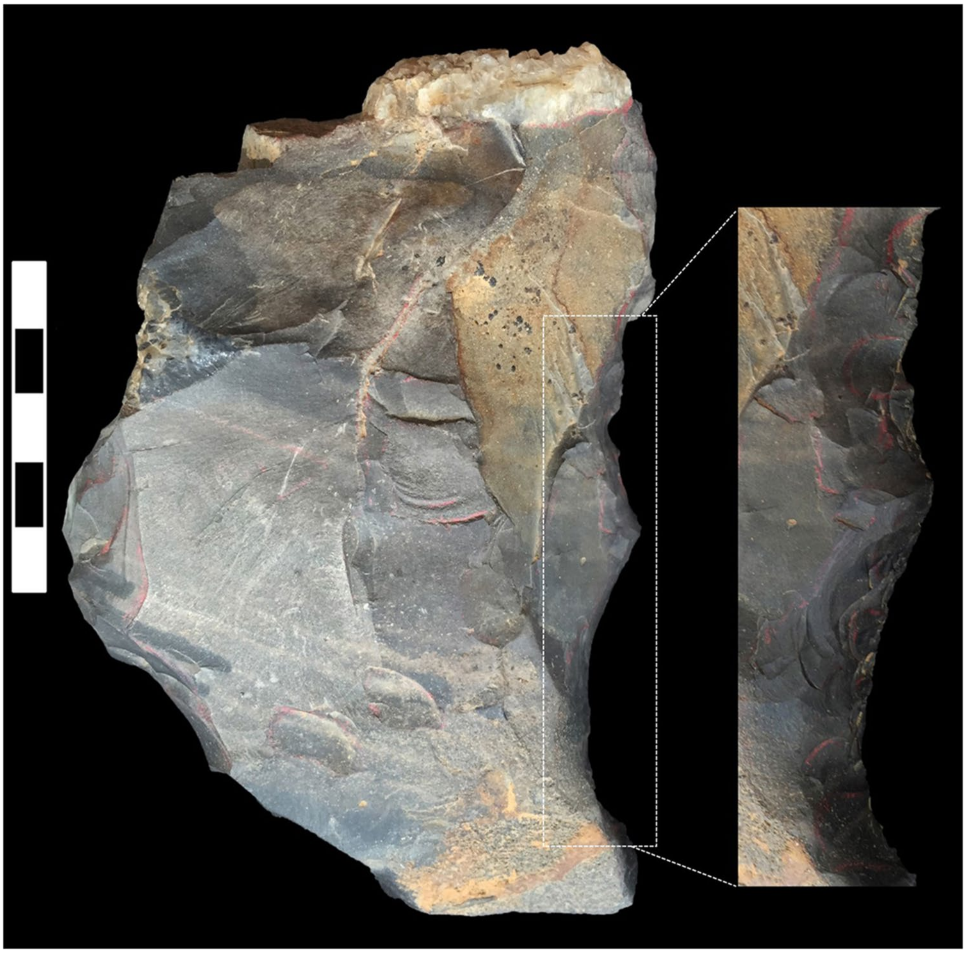


Fig. 16 Selected retouched pieces. (**a**) Denticulate with convex edge; (**b**) Scraper with both concave and convex edge

Fig. 17 Zoomed-in picture of a typical steep edge



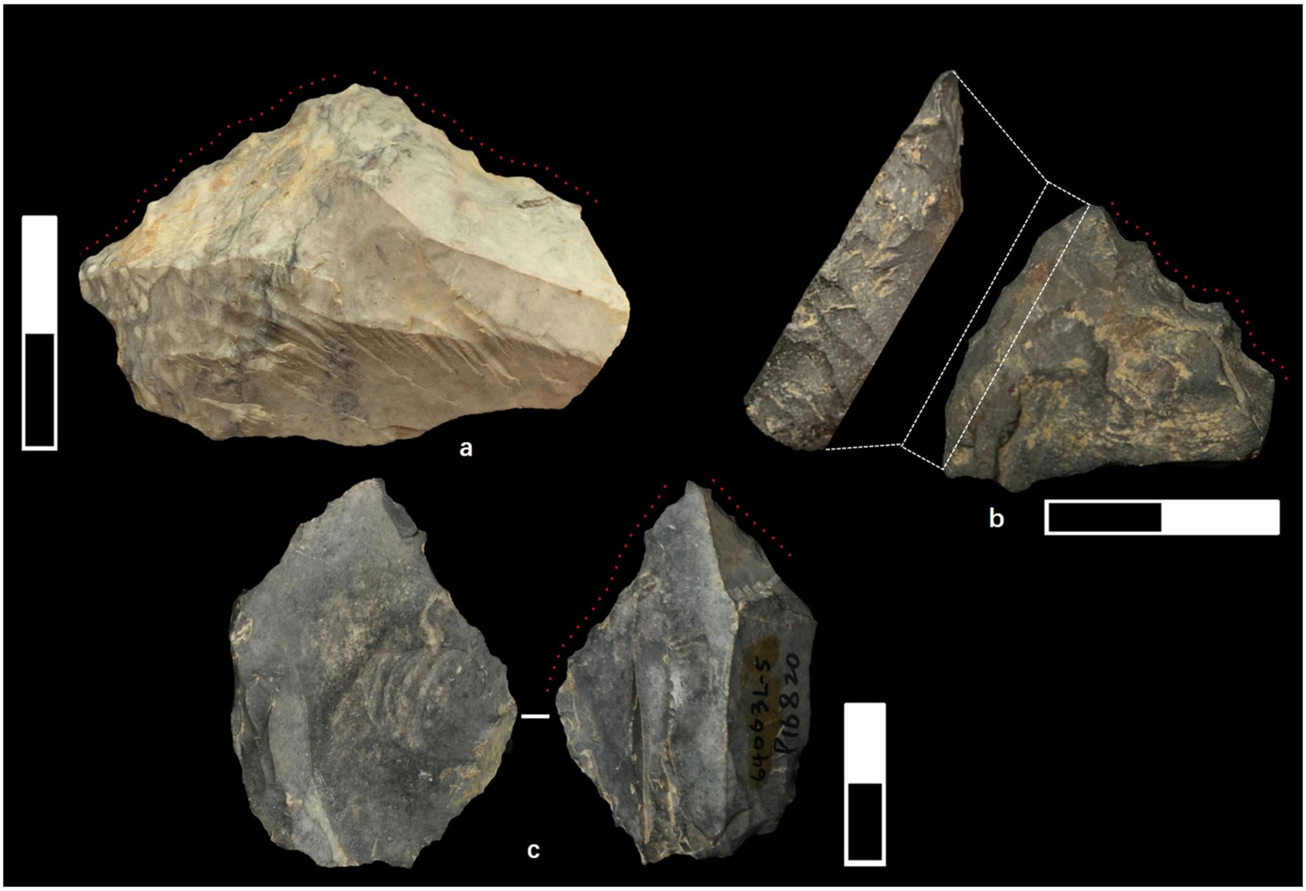


Fig. 18 Selected convergent scrapers. Red dotted lines show the retouch areas

transverse scrapers (Fig. 13b). Endscrapers are a well-defined typology among the retouched pieces, which is relevant with the abundance of Quina retouch (Debénath and Dibble 1994). However, it is important to note that some of the parallel removals on volumetric reduction cores quite resemble endscrapers (Fig. 22). There is no explicit boundary to separate endscrapers whose retouch on a narrow end of a given blank overlap with the definition of volumetric modality. Therefore, we provisionally ascribe them to volumetric exploitation, with caution that this categorization is to fit in current classification system, rather than intention of hominins.

Denticulates are another well-presented tool type, most of which are retouched along a flake's side edges (Fig. 23a, b). The outline of denticulate edges are overall miscellaneous, including straight (Fig. 23c), convex (Fig. 23e, f), concave, and both (Figs. 15d and 23d). The size of denticulates varies, ranging from 20 to 120 mm, with a median length of 60 mm. The retouching approach is standard, formed by contiguous small notches on interior or exterior surfaces.

Borers are also an important element in the tool kit, albeit in broad terms, they belong to Upper Palaeolithic tool groups. Borers are characterized by a pronounced tip achieved through two concaved sides that centralizing and narrowing the middle part (Fig. 24). The size of borers does not show much specialisation, ranging from 20 to 100 mm.

Quina retouch

A large quantity of Quina sidescrapers at Guanyindong (Fig. 25) were found. The retouching scars on these tools form a distinctive stepped morphology, especially where those scars overlapped on the retouched edge (Agam and Zupancich 2020). Quina is recognized through the presence of several attributes: (1) the prevailing steep edges, where the median retouched edge angle of the assemblage is nearly 70° (Figs. 12e and 14c); (2) relatively thick blanks (Fig. 12d, f) that provide high retouch potential (the median ratio of oriented width to oriented thickness = 3, Fig. 9b); and (3) the presence of several retouching phases on artefacts (Hiscock et al. 2009). However,

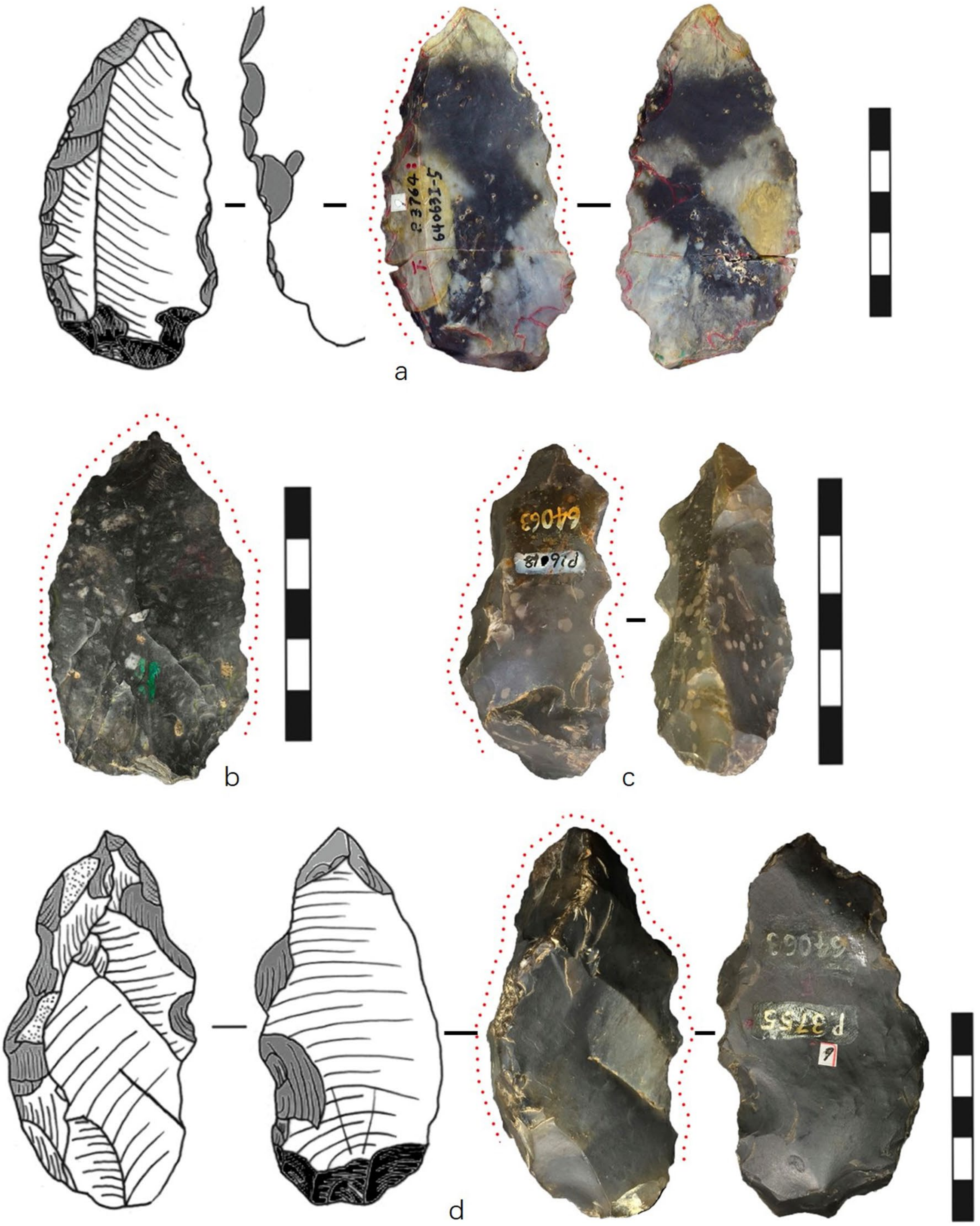


Fig. 19 Selected elongated-pointed pieces. Dark grey color showing the retouches at the 'haft' part, light grey color showing the 'pointed' area. Red dotted lines show the main retouch areas

with a small number of pieces showing typical asymmetry Quina-type flakes with one elongated lateral against a thick face (Bourguignon 1996; Hiscock et al. 2009; Turq 1989, 2000), our current data is insufficient to support a full Quina reduction system.

There is ongoing debate about whether Quina retouch was deliberately produced or whether it was the emergent result of resharpening thick blanks continuously (Dibble 1995; Hiscock and Clarkson 2008; Lin and Marreiros 2021). In other words, the blunt edges may result from multiple functional

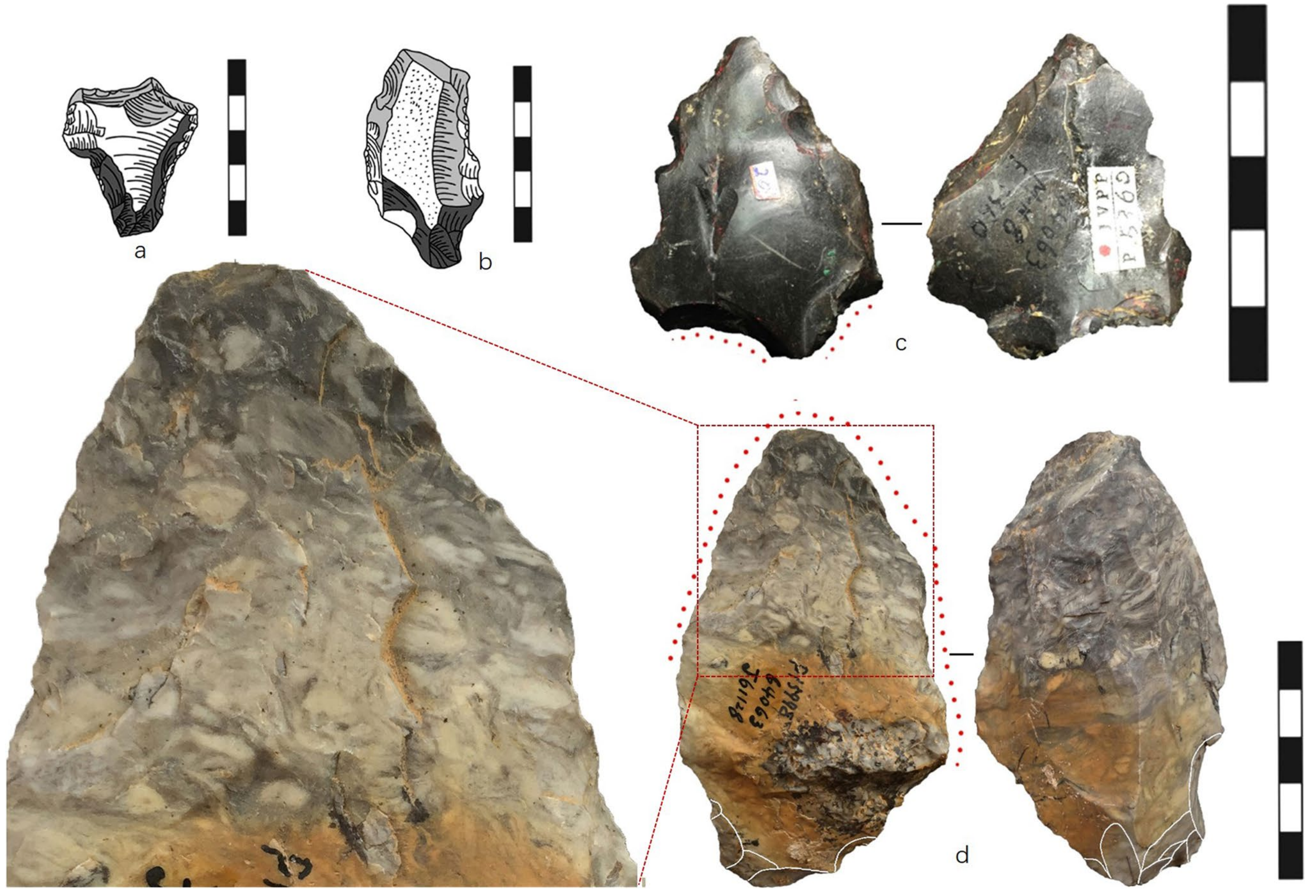


Fig. 20 Selected tanged point with modifications on the haft area. Dark grey color showing the retouches at the 'haft' part, light grey color showing the 'pointed' area. Red dotted lines show the main retouch areas

requirements such as treating organic materials including both animal (hides, meat) and plants (wood) (Hardy 2004; Hiscock et al. 2009; Preysler 2010), or they result from long-lived tools with different retouch intensities. Both situations are possible for the presence of Quina artefacts at Guanyindong, since frequent resharpening and recycling for extending the use-life of tools and demands for blunt edges are evident. Experiments suggest that the making of Quina retouch scars was probably via soft-hammer technique (e.g. Abrams et al. 2014; Rosell et al. 2015). Taking into consideration the consecutive parallel retouches on endscrapers, we do not exclude the possibility of soft-hammer retouching also.

Discussion

The techno-complex at Guanyindong cave

Our findings from Guanyindong suggest technological variation in lithic production during Middle and Late Pleistocene in southwest China. The techno-complex is clearly beyond the classificatory schemes of simple core-flake lithic system. A highly flexible technological strategy at Guanyindong is evident in both core reduction and tool production. These behavioral patterns should not be casually regarded as expedient.

The reduction modes analyzed above exhibit a relatively low frequency within the Guanyindong assemblage. When we exclusively examine the core assemblage, which comprises distinct elements with clear attributions representing reduction strategies, it shows that Levallois, discoidal, volumetric exploitation, and core-on-flakes account for 38.4% of the assemblage (Fig. 4). The proportion decreases to 13% ($n = 33$), if core-on-flake is excluded. Nevertheless, their presence suggests a wide array of core reduction approaches were employed to produce flakes. Because the composition of raw materials remains consistent across all reduction approaches, with chert consistently dominating in every core reduction strategy, showing minimal variability between them, the coexistence of multiple lithic strategies seems to be less related with limitations posed by raw materials, but more responsive to dynamic knapping conditions and specific requirements for blanks. In parallel, the subsequent modifications on blanks also presents a high degree of

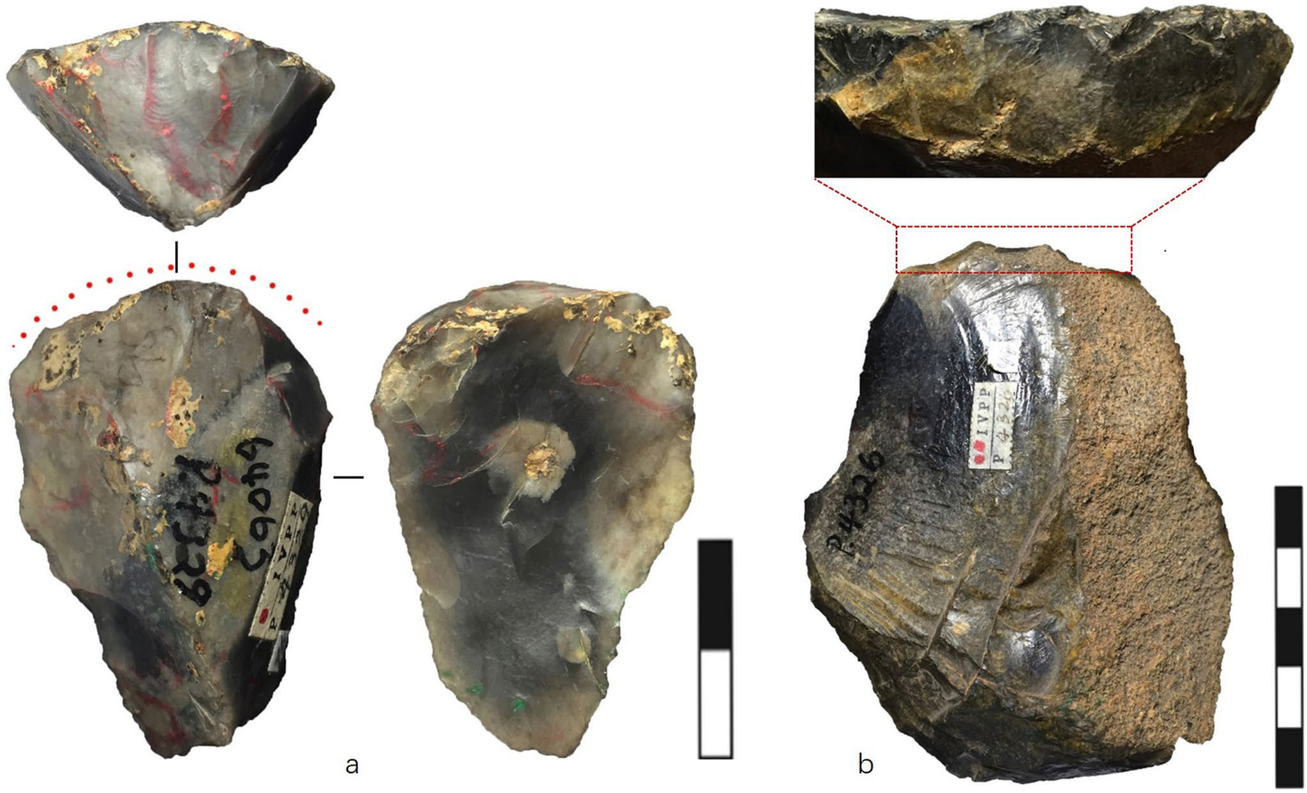


Fig. 21 Selected endscrapers

variability in retouch intensity, localization, and standardization. As a result, a heterogeneous of tool-kit was observed, consisting of implements with simple informal retouch, tools that endured intensive and several retouching cycles, as well as elaborate formal tools.

The most common strategy of lithic production, unquestionably, is polarly striking on a given object, whose convexities and platforms were formed from either natural morphology, or were outcomes of the knapping process. This strategy allows for several rotations whenever a proper configuration for next polar percussion is generated. Polar/unifacial cores with single, double and multiple platforms can be assigned to this batch. They make up more than 60% of the core assemblage. This core reduction strategy is also widely evident in other Palaeolithic industries in China. Polar/unifacial core strategy, along with tools with simple retouch and irregular in size and morphology, point to a long-term consensus of simple core and flake reduction systems and expedient tool curation regarding east Asia MP (Gao 2013; Gao and Norton 2002; Norton et al. 2009; Norton and Bae 2008). In this case, cores are reduced in the similar manner with those from Lower Palaeolithic industries such as Oldowan and Clactonian. The primary scheme for making tools is casual and monotonous, lacking diversity compared with contemporary west. This consensus was grounded by past observations on a large number of archaeological assemblages that chronologically attributed to 300 – 40 ka, such as Xujiayao (Ma et al. 2011), Zhoukoudian Locality 15 (Gao 2000, 2003), Dali (Wu and You 1979; Zhang and Zhou 1984), Dingcun (Jia 1955; Liu 1988; Zhang 1993) and Lingjing (Li 2007), et al. In this paper, we do not attempt to repudiate the widely-observed pebble-tools and simple flake-tool traditions found in many industries. Nevertheless, the data we present here on subtle alternations and innovations indicates that these previous hypotheses should be amended.

Core-on-flakes, the products of recycling flakes as cores, is another major technical concept after polarized production. This kind of technology is used for producing small flakes and is one feature of the MP that has been well-studied in a large number of industries across Europe and the Levant (Goren-Inbar 1988; Hovers 2007; Mathias and Bourguignon 2020; Moncel et al. 2012). Its association with other strategies, such as Levallois, Discoid or Quian, has been identified in many MP techno-complexes (Bourguignon et al. 2004). Mixed assemblages with one dominant production system but accompanied by more categories of flaking methods are found at many sites in western European MP assemblages (Faivre et al. 2017; Hérisson et al. 2016; Malinsky-Buller 2016). At Guanyindong, several reasons may account for the presence of multiple flake production systems and their

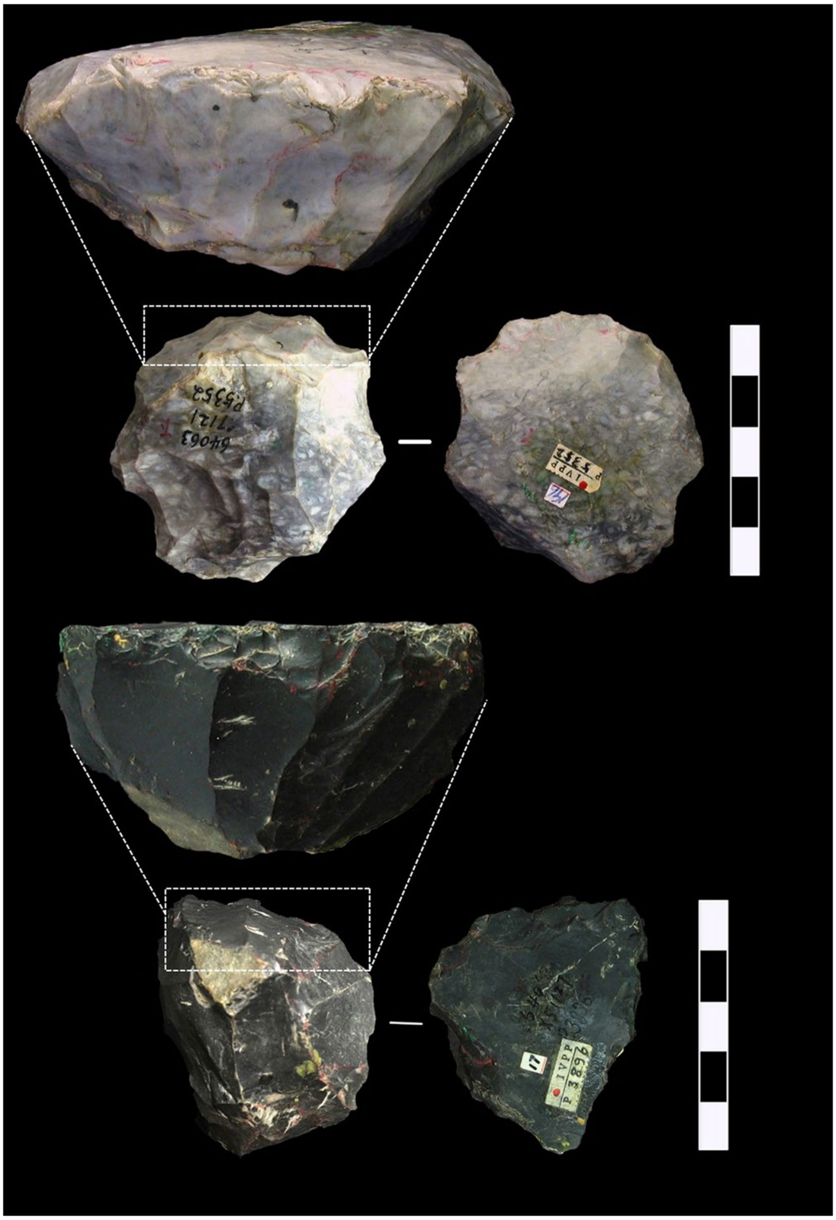


Fig. 22 Pieces with parallel removals

low ratio. For the former case, some widely accepted inferences might be relevant, such as to obtain flakes with specific morphologies, or raw material economization. However, the most important and fundamental mechanism lies in the nature of MP techno-complexes (Kuhn 2013; Richter 2010). For the latter case, except for collection bias which is indicated by low ratio of debris smaller than 20 mm (34.7%), high fragmentation of lithic reduction across time and space is likely lead to the small number of formal types. This segmentation could be attributable to the inherent flexibility and mobility of the MP which is embedded in these lithic technologies (Turq et al. 2013). Another factor driving the products of reduction sequences to be more diffuse relative to the western hemisphere was likely a consequence of low-density, disconnected populations, compared to the relatively higher population and/or high-density conditions of Middle Pleistocene in West Eurasia. The technical knowledge evident at Guanyindong may initially have arisen among the small groups of hominins that implemented technological diversity as they repeatedly occupied the cave during the LMP. Subsequently, the weak and/or irregular patterns of social interconnectedness due to small population sizes and densities may have impeded the spread and establishment of technological innovations (Henrich 2004; Lycett and Norton 2010; Shennan 2001).

Although in small proportion, these approaches should not be interpreted as isolated sequences. Instead, the core reduction approaches may be entangled internally. The flakes produced by a discoid system, for instance, could be transferred into a core-on-flake system (Faivre 2004); the

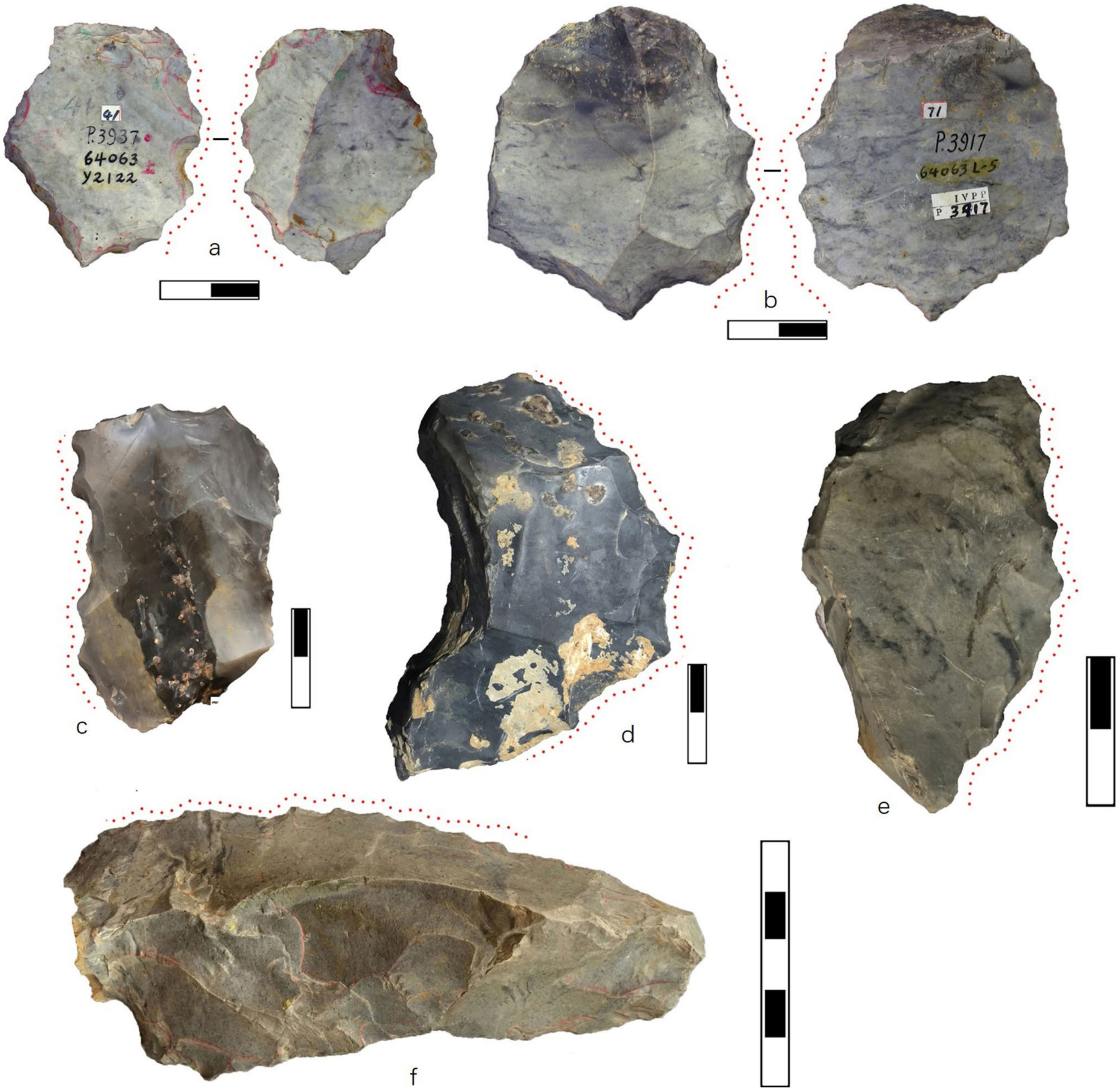


Fig. 23 Selected miscellaneous denticulates

core-on-flake could be transformed into Levallois cores easily (Moncel et al. 2011, 2012). Debitages of these strategies were also likely intertwined, rather than discrete, unrelated sequences. This kind of production system is considered as a 'fluid behavioral set' that is influenced by techniques, raw materials and environmental contexts (Shott et al. 2011). As indicated above, this perplexity is broadly documented in many sites, especially in Europe, and described as a 'fragmented character' (Turq et al. 2013). We propose this concept may be relevant to understanding the Guanyindong hominins also.

The high-mobility of Quina and Discoid is inherent both in their initial reduction and in the way their tools are curated (Delagnes and Rendu 2011; Hiscock and Clarkson 2009; Hiscock et al. 2009). The Quina blanks were produced without high investment in core preparation. This enables them to rapidly replace worn tools by creating a new practicable blank, usually having an asymmetrical and thick cross-section to provide the blank with adequate retouch potential. Hence, this kind of blank is well adapted to a long-use life that can be repeatedly resharpened or recycled. In addition, Quina tools are potentially multi-purpose since they can be

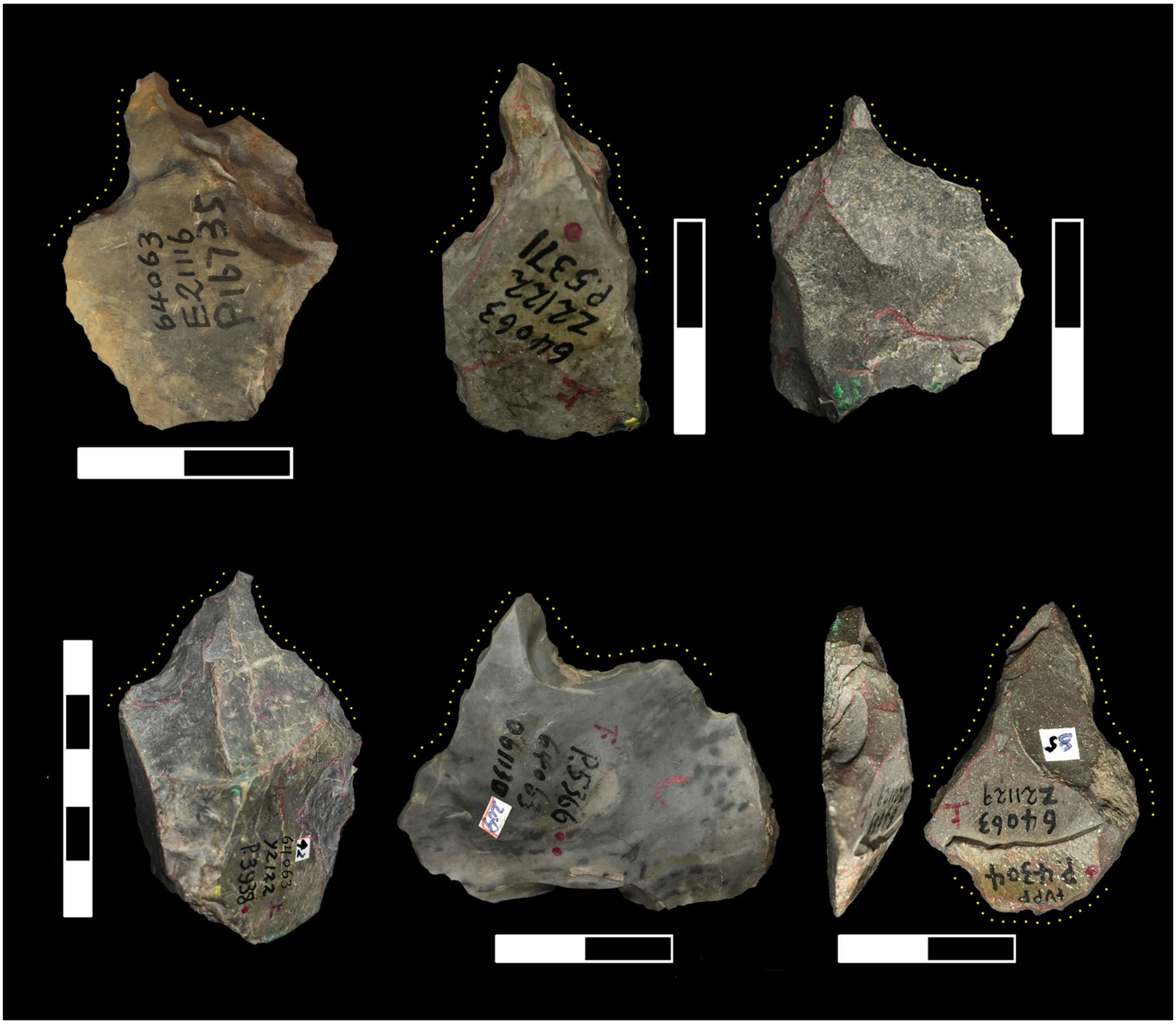


Fig. 24 Selected borers. The retouches forming tips are shown in yellow dots

modified by several different retouching phases, reflecting different functions, before they are discarded. The combination of low investment in core preparation, long use-life and high versatility of the blanks help hominins adapt to various environments when exploring an expansive landscape.

Likewise, discoid methods involve a relatively low degree of requirements, compared with the elaborate preparation of Levallois system, for technological investment (Delpiano and Peresani 2017; Picin and Vaquero 2016), and relatively high productivity (since it does not need re-preparation between each reduction phase). In addition, the discoidal blanks are versatile and recyclable, with a high rate of flakes being transformed into tools and the multiple phases of tool retouching or maintenance at Guanyindong. Therefore, combined with the transport capacities and tool curation and maintenance qualities for both Quina and discoid, their potential for serving as 'personal gear'(Binford 1979) or 'individual provisioning'(Kuhn 1995) mode is high, revealing long and complex sequences of mobility patterns. Moreover, it should be noted that although it offers limited insights into the diversity of core technology due to its contextualization within varying conditions of technological organization, site functions, and subsistence strategies spanning from the Lower to Upper Palaeolithic periods (e.g. Bar-Yosef and Belfer-Cohen 2013; Harmand et al. 2015; Leakey 1971; Zhu et al. 2018), unifacial reduction, which is the dominant the reduction pattern observed in Palaeolithic assemblages, also characterizes the knapping approaches at Guanyindong, indicating influences of place provisioning strategies (Kuhn 1995; Nelson 1991).

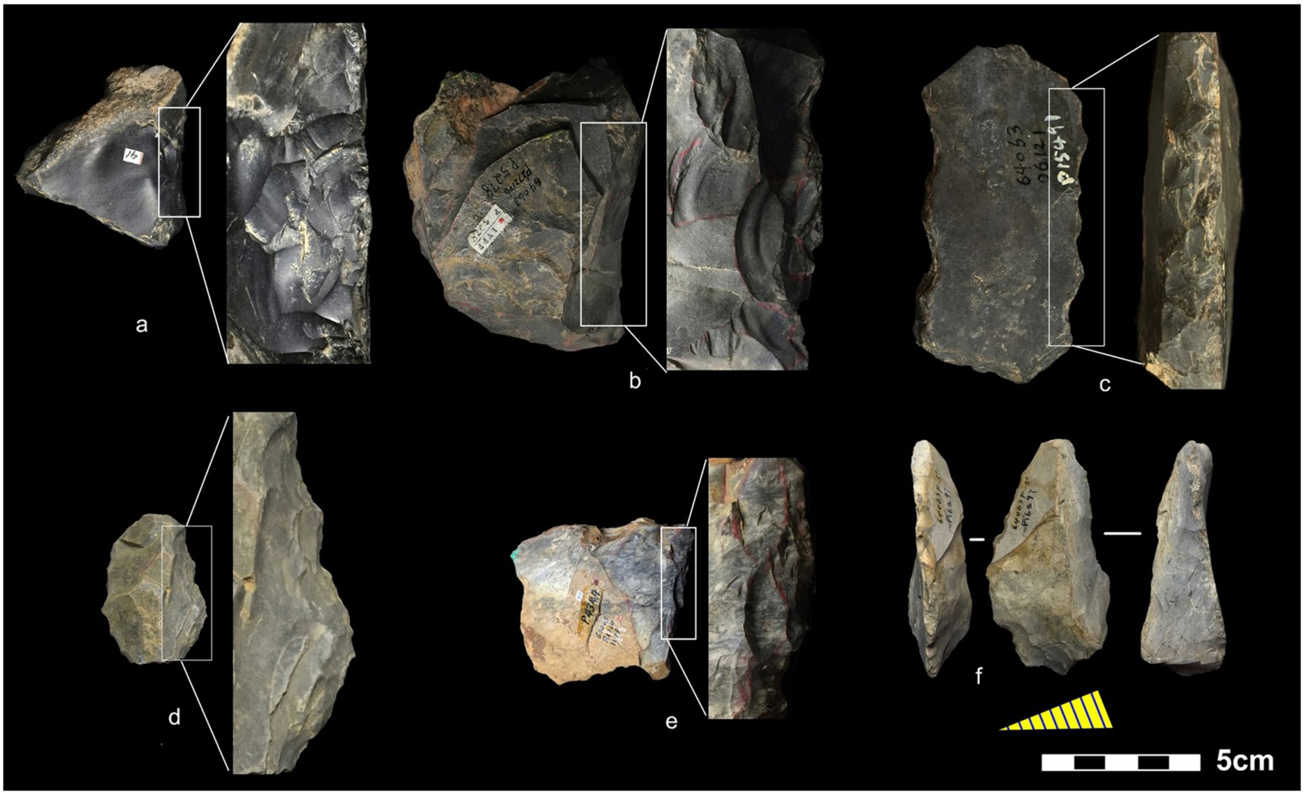


Fig. 25 Quina tools and retouched blank. (**a**-**e**) Quina scrapers with stepped retouching scars that obtained from several phases of retouching. The white boxes on each tool edge show the areas of which the zoomed details on the right. (**f**) A blank, possibly achieved from Quina reduction, and then was retouched into scraper, the yellow oblique triangle below is the cross-section of the blank

In terms of raw material procurement, as mentioned before, the distance (2–6 km) indicates a restricted foraging scope. There appears a conflict between high mobility strategies as indicated by lithic technologies and restricted raw material procurement range as suggested by source distance. However, the correlation between source distance and excursion range has been questioned (Agam 2020; Delage 2007; Ekshtain and Tryon 2019). On one hand, it is difficult to point directly at the source of acquisition of raw material sometimes, as not all the outcrops are yet discovered and documented. On the other hand, mobility patterns may be more related to seasonal organization, hunting activities and food consumption recycled in an annual pattern (Delagnes and Rendu 2011). Short raw material distances may not necessarily indicate the full foraging range of a group (Kelly 1992).

In addition to the flake production diversity, the curation of tool-kits also confirms the attribution of an authentic MP techno-complex. The dominant unstandardized flake-tools blending with elaborate formal tools and Quina retouch that not only originated from MP culture-groups but also encompass Upper Palaeolithic tool types, denote a distinct strategy of tool modifications that is far from Mode 1 and Mode 2 typologies, as well as Lower Palaeolithic core-and-flake industries, such as Clactonian (White 2000; Wymer 1974). The selection of diverse technical concepts and procedures for tools in the MP industry at Guanyindong was contingent on numerous factors. An inevitable fact of any lithic assemblage is that it was structured by many diachronic processes, such as sedimentary features, geologic events, and palimpsests. Other aspects concerning the MP's technological nature, choices (cultural factors), raw materials economy, on-site activities, mobility, and the environment (Dibble 1995; Rolland and Dibble 1990) certainly also led to the diverse circumstances in which stone artefacts were made and used at Guanyindong over hundred thousand years.

An important limitation to our interpretation of the Guanyindong assemblage is the incomplete provenance data in the excavation records. Our previous work established that artefacts were produced in two discrete periods, one clustered at around 170-160 ka (MIS 6) and the other clustered at 90 – 80 ka (MIS 5). The large chronological gap (~ 80–90 ka) between the two periods is due to an erosional hiatus in the deposits. Fortunately, the new OSL results suggest a continuous occupation, spanning from MIS 6 to MIS 5 (Hu et al. 2023b). But with the current data, the field recording methods employed in the initial excavation mean that we cannot confidently allocate most artefacts to one specific phase. This also limits our ability to make robust claims about change over time, though our analysis indicates that the technological attributes show little difference between the upper and lower layers (see SI from Hu et al. 2019b). Hence, the diversity described here, on one hand, could either represent coexistence of multiple technological strategies in a certain time or, on the other hand, a sequence of technological changes over time, similar to that widely observed at sites in Eurasia (Delagnes and Meignen 2006). However, given the nature of the cave deposit and reference of analogous sequences (Faivre et al. 2017), we tend to interpret the combination of different systems as reflecting disturbances between different non-synchronous assemblages.

Although the lack of precise excavation information hampers the discussion on technological changes through time, but the multiple technological concepts for flake production during MP period is not altered and weakened. We hope future fieldwork in the region will shed light on ambiguities in technological coexistence or developmental trajectories.

Implications for Chinese Middle Palaeolithic

In contrast to the fine-grained behavioral evidence and high-resolution technological studies from a wide range of MP sites in West Eurasia, the data from East Asia are currently sparse and reports are typically coarse-grained. To date, many paleolithic sites in southwest China have been found (Cai 1991; Cao 1978; Hu et al. 2019c; Wu 1975; Zhu and Ji 2011), though only a few of them, such as Guanyindong and Panxian Dadong (Zhang et al. 2015), have been securely dated to the late Middle Pleistocene period. Evidence of various traits of MP technologies in Guanyindong, might be a starting point of a full suite of technological abilities among hominins in this area, or otherwise an isolated local adaptation or small-scaled cultural diffusion.

Nevertheless, we reject the opportunistic null hypotheses to explain the diversity of Guanyindong industry, in light of its complexity and consistency. Actually, several recent re-studies of previously excavated archaeological assemblages suggest variations and gradual development in terms of lithic technologies. After reanalyzing the Dali assemblage, Li and Lotter (2019) detected relatively complex technologies of tool production from predominantly expedient flaking strategy, such as formal discoidal flaking system, and skilled manipulation of small quartz cores. Similarly, a diversity in tool types was revealed by Li et al. (2019b) after re-examining the Lingjing lithic assemblage, and inspired them to propose the term ‘Chinese Middle Paleolithic’ to set the complexity and balance the similarity and disparity with MP/MSA sites in western Eurasia and Africa. Updated luminesce dating results from the Nihewan basin show that many previously assigned Palaeolithic sites are actually anachronisms (Guo et al. 2016, 2017; Lei et al. 2022), and should be re-assigned as MP complexes. Xinmiaozhuang Locality 1 is another site that was re-dated to 63–75 ka lately (Wang et al. 2021). Its techno-complex features simple core-and-flake incorporated with ‘complex’ elements, such as discoidal cores, elongated flakes, and ‘Mousterian-like’ triangular points and scrapers, providing more evidence that contrast to prevailing views of Chinese MP as simple and monotonous.

Our data in this paper further challenge this these views by presenting a more integrated and comprehensive combination of technological concepts during MP in East Asia. We propose that the lithic techno-complex at Guayindong, if not equivalent, is comparable with MP/MSA sites in western Eurasia and Africa. The MP in China and East Asia should not be regarded as merely simple, technological laggard or stagnant since Lower Palaeolithic. Instead, Chinese MP industries should be treated without prejudice case by case.

Conclusion

Indicators of technological flexibility, including the Levallois concept, Discoid, core-on-flake, and volumetric exploitation, as well as the capacity for making formal tools, although varying in size, morphology and quality, remain essentially *MP attributions*. They indicate that the appearance of Levallois products at Guanyindong was not an isolated technological mutation. But it is one of the variants resulting from hominins that adopted a set of complex flake-making gestures for MP tool-kits when managing their daily routines.

The absence of human fossils dated to the same period in southwest China limits speculation about which hominin species produced the Guanyindong assemblage. However, anthropological studies in and/or near this region have provided some possibilities. The Denisovan fossil found in Baishiya, dated to 160 ka, provides the first evidence of Denisovan activity in East Asia (Chen et al. 2019). The appearance of modern humans (Bae et al. 2014; Chen et al. 2019; Curnoe et al. 2021; Liu et al. 2010, 2015; Martinón-Torres et al. 2021; Sun et al. 2021), and shared morphology with the Neandertals found on crania from Xuchang (Li et al. 2017) suggest that although ascertaining the Guanyindong hominins is difficult, isolated and unprecedented hominin taxa are unlikely.

Currently, the limited number of available assemblages for the Palaeolithic in the Eastern hemisphere does not allow for a robust clarification of relationships among technical behaviors or resolution of the debate on where and when the common technological ancestor for East Asian and Western MP may be found, and what circumstances lead to the appearance of MP technologies in East Asia (e.g. direct descent from a common technological ancestor or recent convergent technological evolution after substantial divergence). Future research and re-studies of other MP sites in this region focusing on establishing more detailed behavioral patterns and firm timeframes are crucial to better understand the MP in East Asia and to evaluate models of technological convergence or transmission.

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Author contribution B.L., Y.H., Y.-M.H., and W.-W.H. conceived and coordinated the study. Y.H., B.L. and Y.-M.H. conducted the fieldwork. Y.H., B.M., Y.-M.H., and H.-L.L. conducted the stone artefact analysis. Y.H., B.M., H.-L.L. and Y.-M.H. wrote the manuscript, with contributions from the other authors.

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Declarations

Competing interests The authors declare no competing interests.

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