Journal of Paleolithic Archaeology (2024) 7:25
https://doi.org/10.1007/s41982-024-00189-9

RESEARCH

Beyond Large-Shaped Tools: Technological Innovations and Continuities at the Late Early Pleistocene Assemblage of El Barranc de la Boella (Tarragona, Spain)

Diego Lombao[1,2,3] · Juan I. Morales[2,4] · Marina Mosquera[2,4] · Andreu Ollé[2,4] · Palmira Saladié[2,4,5] · Josep Vallverdú[2,4,5]

Accepted: 15 July 2024

Abstract

The emergence of the mode 2 technocomplex, traditionally characterized by the development of large cutting tools (LCTs) or standardized large-shaped tools, has also implied a range of new technological behaviours. These include enhanced raw material management, more sophisticated knapping strategies, and transport patterns, among other innovations. Unit II of the localities of La Mina, El Forn, and Pit 1 in El Barranc de la Boella (Tarragona, Spain) — dating back to between 0.99–0.78 million years ago — contains the oldest mode 2 assemblages in the European subcontinent and represents an exceptional opportunity to examine the technological features associated with the appearance of LCTs in Europe and to provide clues to shed light to different hypotheses about their appearance. The presence of functionally diverse but environmentally similar localities enables a study of behavioural flexibility and technological variation, marking a critical contribution to understanding early human technological evolution. Our research focuses on the technological behaviours of hominins in unit II of Pit 1, La Mina, and El Forn at Barranc de la Boella, examining five keys technological aspects such as (1) raw material management, (2) core reduction sequences, (3) reduction intensity, (4) large flake production, and (5) the spatiotemporal integrity of reduction sequences. We compare these behaviours with those observed in mode 1 (~ 1.8–0.9 Ma) and early Middle Pleistocene (~ 0.78–0.6 Ma) assemblages across western Europe. Our findings reveal significant advancements and anticipatory behaviours at El Barranc de la Boella, such as the use of procedural templates for core reduction strategies and the production of large-shaped tools governed by principles of gestural economy, and also the existence of different reduction sequences in different raw materials according to specific purposes. The technological behaviours observed at El Barranc de la Boella seem to be more indicative of population dispersals rather than local evolutionary developments from mode 1 technologies. The non-linear evolution of core knapping strategies, along with the variability in large-shaped tool types, suggests multiple waves of hominin dispersals into Europe during this crucial period. We propose that El Barranc de la Boella may represent an early dispersal of the Acheulean from Africa around 1.4 million years ago, potentially connected to assemblages such as 'Ubeidiya. This study underscores the complexity of lithic technology during this period and contributes significantly to our understanding of the complex emergence and adoption of new technological behaviours in European early mode 2 assemblages, extending beyond the mere appearance of LCTs.

Keywords El Barranc de la Boella · Mode 2 · Acheulean · Core knapping strategies · Technological behaviours · Reduction intensity · Late Early Pleistocene

Introduction

The presence of large cutting tools (LCT) or standardized large-shaped tools has traditionally been considered the best cultural marker for the mode 2 or Acheulean (e.g. Clark, 1969; Finkel & Barkai, 2018; Hodgson, 2015; Moncel et al., 2016; Sharon, 2009). Among them, the handaxe, due to its easy recognition, wide geographic distribution, and its ubiquity in the archaeological record over time, has been the focus of numerous technological studies. Several authors have emphasized the involvement of complex cognitive capabilities in the production of these large tools, among other LCTs, such as the ability to impose shapes also knows

Extended author information available on the last page of the article as mental templates (Gowlett, 1986). This is considered a significant advance in cognitive capabilities and technical skills compared to preceding technocomplexes such as the Oldowan or mode 1 (Corbey et al., 2016; Goren-Inbar, 2011; Gowlett, 1986; Stout, 2011; Stout et al., 2015; Wynn, 2002). Thus, this iconic tool has been considered a milestone in the evolution of the technological behaviour of the genus *Homo* and an insignia of cognitive complexity.

These reasons explain the proliferation of studies measuring variability of handaxes. This includes the study of their shapes (García-Medrano et al., 2018, 2020a, b; Herzlinger & Grosman, 2018; Herzlinger et al., 2017; Hoggard et al., 2019; Key & Lycett, 2017) and their relationship with other factors, such as raw material properties (Ashton & McNabb, 1994; Jones, 1979), reduction intensity (McPherron, 1994, 1995, 2000; Shipton & Clarkson, 2015a), and other technological aspects, such as symmetry (Cole, 2015; Hodgson, 2009, 2011, 2015; Hoggard et al., 2019; Ioviţă et al., 2017; Machin et al., 2007; Mcnabb & Cole, 2015). Additionally, the gestures involved in their production have been studied (Cueva-Temprana et al., 2019; Geribàs et al., 2010) as well as the social transmission mechanisms necessary to transfer the knowledge to produce them (Putt et al., 2014), among many other aspects (Fedato et al., 2020; Key & Lycett, 2017; Key et al., 2016; Muller & Clarkson, 2016; Muller et al., 2017; Silva-Gago et al., 2022).

Nevertheless, handaxes are only one type of standardized large-shaped tools, which also include picks, cleavers, knives, and others. The production of these tools represents only one facet of polyhedral and variable human behaviour. Therefore, although the presence of LCTs — regardless of their frequency — is the main characteristic of the emergence of this technocomplex (de la Torre, 2009; de la Torre & Mora, 2014, 2020; Gowlett, 1986; Stiles, 1980, 1991), there are other elements that allow for further definition and characterization of the behaviours associated with the mode 2 (de la Torre, 2009, 2011; de la Torre & Mora, 2018; de la Torre et al., 2008). This perspective has partially overcome the LCT-centric view and challenged the static and immovable vision of the mode 2 (Gallotti & Mussi, 2018).

New (Mode 2) Behaviours in Africa

Therefore, it has been argued that in early African mode 2 assemblages (approximately 1.7–1.5 Ma), such as Gadeb and Melka Kunture (Ethiopia) in East Africa, the ability to produce LCTs has been accompanied by several new technological behaviours, including (1) greater complexity in raw material management, (2) diversification and greater complexity of knapping strategies, (3) the ability to produce large-size flakes (> 10 cm), (4) temporal and spatial fragmentation of reduction sequences, and (5) changes in land-use and environmental management (de la Torre, 2011, 2016; de la Torre & Mora, 2018; Gallotti, 2013). These behavioural changes would represent more complex or efficient ways of adapting to the environment (Antón et al., 2014; Cachel & Harris, 1998; Gowlett et al., 2012).

However, there is no techno-typological homogeneity in early LCTs. Additionally, their appearance in the archaeological record does not necessarily imply changes in favour of all the behaviours described above. First of all, it appears that the LCTs are not typologically or technically homogeneous: In FLK West (Diez-Martín et al., 2016; Sánchez-Yustos et al., 2017b), some LCTs exhibit a markedly symmetrical character, while in other East African sites, such as Konso (Beyene et al., 2013), Gona (Semaw et al., 2018), and Kokiselei 4 (Lepre et al., 2011; Roche et al., 2003), this feature is absent. However, these assemblages share certain characteristic features, such as an association between the presence of LCTs and large flakes.

In addition, the dynamics reflected in core reduction strategies do not seem to represent a simpler scenario. In some cases, the knapping methods reflect complex volumetric management, such as at the SHK and BK sites at Olduvai (1.5 Ma) (Sánchez-Yustos et al., 2017a) or in the Olduvai BK and TK Upper Floor (1.35 Ma) (de la Torre & Mora, 2005). This complexity in core management is related to systematic preparations of the percussion platforms in sites such as Melka Kunture (Gallotti, 2013) or to the presence of bifacial hierarchical centripetal cores in Peninj (de la Torre, 2009; de la Torre et al., 2008).

However, in other assemblages such as Gadeb, the core reduction sequences are generally expedient and quite simples, with the exception of Gadeb 2E, where the knapping methods are more structured (de la Torre, 2011). Moreover, in both Gadeb and Peninj, knapping strategies remained unchanged regardless of the LCT presence (de la Torre, 2009).

This variability in technological behaviour can be identified in other regions such as South Africa. For instance, in the Sterkfontein site, the presence of LCTs is linked to differential raw material management. Conversely, in different test pits at Rietputs 15, there is a notable diversity in core reduction strategies. Some assemblages, such as Artefact Collection Pit, employ simple knapping methods (Kuman & Gibbon, 2018). In contrast, more organized knapping strategies have been documented in other assemblages, such as Pit 5 at Rietputs 15 (1. 3 Ma) (Leader et al., 2016) and Canteen Kopje (1.51 Ma) (Leader, 2014). The complex volumetric management of cores are closely associated with differential raw material management (Leader et al., 2016).

Outside Africa, at Attirampakkam (Indian subcontinent) (1.51 ± 0.07 Ma) (Pappu et al., 2011), studies point to LCTs appearing accompanied by fragmentation of reduction sequences, hierarchical organization of knapping sequences, the ability to produce large flakes, and a higher degree of planning, reflected in the management of raw material in a scenario of scarce lithological resources (Kumar Akhilesh & Pappu, 2015; Pappu & Akhilesh, 2019), in 'Ubeidiya (1.5/1.4 Ma) in the Levant (Bar-Yosef & Goren-Inbar, 1993), the appearance of LCTs occurs in parallel with a very marked raw material management and a fragmentation of the reduction sequences (Herzlinger et al., 2021).

What About Western Europe?

In western Europe, the presence of certain large-shaped tools in the lithic assemblages of El Barranc de la Boella (La Canonja, Tarragona, Spain) has made it possible to classify this archaeological site as mode 2 or Acheulean, anticipating the arrival of this technocomplex until approximately 1 Ma ago and reducing the chronological gap between Europe, Asia, and Africa (Mosquera et al., 2016; Vallverdú et al., 2014b). In this regard, El Barranc de la Boella appears to be an early mode 2 site, with particular features in terms of production of large-shaped tools (mainly picks) that have been linked to a so far undetected African dispersal to Europe, possibly linked to the one represented by sites as 'Ubeidiya, given the affinities between the two assemblages (Ollé et al., 2023).

This, together with the discovery and review of other assemblages, such as the level US4 of the Bois-de-Riquet (France) (Bourguignon et al., 2016a; Viallet et al., 2022), the Notarchirico sequence (Carpentieri et al., 2023; Chavaillon & Berthelet, 2004; Moncel et al., 2019, 2020b; Santagata et al., 2020), La Noira Stratum a (Despriée et al., 2015; Hardy et al., 2018; Moncel et al., 2016, 2020a, 2021), and Moulin Quignon (Antoine et al., 2019), has made it possible to draw a more complex scenario for the appearance of the Acheulean — or Acheuleans (Moncel et al., 2016) — in western Europe, as well as to characterize the lithic assemblages associated with these occupations.

Once again, the analysis of these assemblages has mainly focused on the techno-typological study of LCTs and on the reconstruction of their *chaînes operatóires* or reduction sequences (García-Medrano et al., 2022; Ollé et al., 2023; Viallet et al., 2022). However, changes in technological behaviour that may be associated with the appearance and presence of LCTs have not yet been studied in depth, although some advances have been made, especially related to the evolution of technological behaviour throughout the Middle Pleistocene, deepening changes in land-use patterns, and the development of new core technologies (Moncel et al., 2021).

In this regard, El Barranc de la Boella is an exceptional window to evaluate the technological changes that accompany the appearance of LCTs in Europe, providing clues about their appearance in Europe (in situ evolution, diffusion, or arrival). Moreover, the coexistence of three functionally diverse localities with similar ecological contexts (Mosquera et al., 2015; Pineda, 2018; Pineda et al., 2015, 2017b) allows us to evaluate behavioural flexibility in this period through the study of inter-assemblage variability, representing a step forward in the study of technological behaviour during this crucial period of human evolution.

In this study, we investigate the technological behaviours exhibited by these hominins at the sites of Pit 1, La Mina, and El Forn within El Barranc de la Boella. Our analysis covers five main aspects: (1) raw material management and blank selection, (2) core knapping strategies, (3) reduction intensity and volumetric depletion, (4) production of large flakes, and (5) spatiotemporal integrity of the reduction sequences. The goal is to characterize the range of behaviours of these assemblages beyond the presence of large-shaped tools and to define their position in relation to the archaeological record of the Early Pleistocene mode 1 in Europe and the mode 2 assemblages of the early Middle Pleistocene, in order to address their possible origins as either a local evolution or the arrival of new populations.

El Barranc de la Boella site

The El Barranc de la Boella site is an open-air site located in the NE of the Iberian Peninsula, approximately 5 km from the current coastline of the Mediterranean Sea (Vallverdú et al., 2014b) (Fig. 1). The sedimentary sequence is approximately 9 m thick and has six lithostratigraphic units, named I-to-VI, from base to top. A detailed stratigraphic description can be found in Vallverdú et al. (2014b). To date, excavation has occurred at three different localities, sharing the same lithostratigraphic units: Pit 1 (P1), with an excavated area of 210 m^2; El Forn (EF), with an excavated area of 40 m^2 in front section of P1; and La Mina (LM), with an excavated area of 250 m^2 and located 180 m from P1. Unit II concentrates the highest density of archaeological materials and reaches up to 2 m of sedimentary thickness. Ollé et al. (2023) offer a detailed state of the art of the fieldwork development in these localities.

Biostratigraphic age estimations, paleomagnetic and cosmogenic nuclide analyses from unit II provide a chronological range of 900–780 ka (Lozano-Fernández et al., 2014; Vallverdú et al., 2014b), establishing the three localities as penecontemporaneous (Mosquera et al., 2016; Vallverdú et al., 2014b).

Different archaeological levels have been identified at each locality within unit II. Thus, at EF, up to six archaeological levels (2 to 7) have been described, while five (1 to 5) at LM, and two (2 and 3) at P1 (Vallverdú et al., 2014b). However, levels 5, 6, and 7 from EF and level 3 from P1 are exclusively palaeontological.

In all three localities, the lithic assemblage encompasses a diverse range of raw materials. These raw materials are

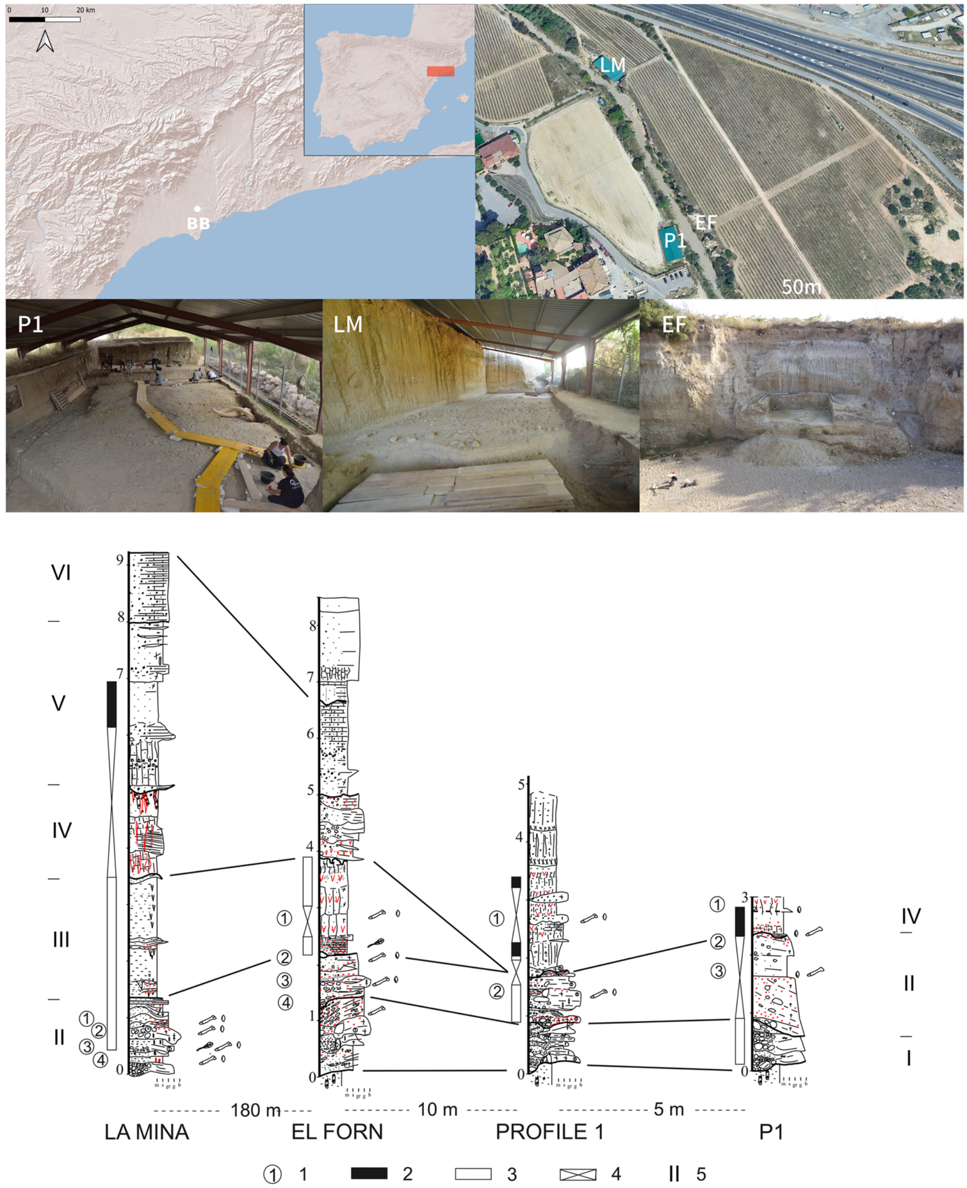

Fig. 1 (Upper left) location of El Barranc de la Boella (BB), (upper right) location of each locality (LM, La Mina; EF, El Forn; P1, PIT 1 and profile 1). Medium line: general views of each locality. Bottom: lithostratigraphic correlation of the BB localities (modified from Vallverdú et al., 2014b). Legend: (1) archaeopaleontological levels (Arabic numerals), (2) normal magnetic polarity, (3) reverse magnetic polarity, (4) undetermined magnetic polarity, and (5) lithostratigraphic units (Roman numerals). The red v-shaped lines and dots represent red-yellow cryptocrystalline segregations (mottles)

sourced locally in secondary outcrops, within a radius of less than 5 km, and can be easily obtained from the Quaternary deposits upon which the fluvio-deltaic formation evolved (Mosquera et al., 2016). Among them, it has been possible to document metamorphic rocks (different varieties of schist and quartzite), sedimentary rocks (chert, limestone, sandstone, and lydite), igneous varieties (granite and dioritic porphyry), and vein quartz, in the form of globular cobbles and pebbles very variable in terms of size and shape. The globular shape depends on the distance from the primary outcrop from which they originated (Ollé et al., 2023).

In terms of land use, El Barranc de la Boella offers an environment rich in resources such as game, plants, water, and lithological materials that were easily accessible to hominins (Pineda et al., 2017b). This, together with the type of occupations, leads to an interpretation of the three localities as supply sites. Taphonomic and zooarchaeological studies indicate a direct correlation between the intensity of hominin activity and the abundance of biotic resources. Levels where higher hominin frequentation is inferred exhibit a greater variety of identified animal taxa, as seen in level II.2 of LM. These levels also show a higher presence of other predators, reflecting scenarios of high competition (Pineda et al., 2017b). This implies that the intensity of hominin occupations or activities is likely linked to the availability and abundance of resources, regardless of the presence of other predators, which has been interpreted as a high adaptive responsiveness and flexibility to different contexts and environmental fluctuations (Pineda, 2018).

Pit 1

Level II.2 of P1 has been interpreted as a kill-butchering site (Mosquera et al., 2015) representing a single event of *Mammuthus meridionalis* carcass exploitation, indicating a high temporal resolution of the context (Mosquera et al., 2015; Ollé et al., 2023; Saladié et al., 2008; Vallverdú et al., 2008, 2014b). *Mammuthus meridionalis* remains correspond to a single adult individual —although a tooth fragment from a neonatal individual has been also identified — in anatomical association and represented mainly by cranial and dental remains. Of interest is the presence of two rib fragments with possible cut marks (Mosquera et al., 2015). Although the high degree of the effect of lixiviation makes it difficult to correctly characterize bone surface modifications, recent approaches have proposed their anthropic origin (Pineda et al., 2019). Both the accumulation of remains and the absence of the most nutritive parts suggest that this individual died in situ or near the site where it was recovered. Although, neither the strategy in the access to the carcass nor the cause of death of this proboscidean has been established (Mosquera et al., 2015; Vallverdú et al., 2014a). Beyond *Mammuthus meridionalis*, there is also occasional presence of other species such as *Dama vallonetensis* and *Equus altidens* (Mosquera et al., 2015).

The lithic assemblage of level II.2 consists so far of 428 pieces (Table 1), and it is composed mainly of knapping products (flakes, fragmented flakes, and flake fragments), retouched flakes, cores, as well as hammerstones, percussive material and knapping fragments. The large-shaped tools (which includes large cutting tools and the groups of heavy-duty tools (sensu Isaac, 1977) especially the picks ($n=6$) (Ollé et al., 2023)) stand out within the assemblage.

La Mina

In unit II of LM, a large number of macrofaunal taxa have been recovered, including cervids (Megacerini indet., *Dama vallonetensis*, *Capreolus* sp.), equids (*Equus altidens*), as well as megaherbivores (*Hippopotamus antiquus*, *Mammuthus meridionalis*) and carnivores such as *Ursus deningeri*, *Canis mosbachensis*, *Panthera* sp. (large), *Lynx pardinus*, and *Vulpes* sp. (Madurell-Malapeira et al., 2019) to which must be added the presence of hyena, inferred from its coprolites and taphonomic modifications attributed to this taxon (Pineda et al., 2017a). *Macaca sylvanus* cf. *fiorentina* was also identified (Fidalgo et al., 2023).

The lithic assemblage from La Mina is composed by 435 pieces, dominated by flakes, fragmented flakes and flake fragments, cores, retouched flakes (mainly carinated denticulates and notches), chopper-cores, as well as hammerstones, percussive material, and knapping fragments (Table 1).

Despite the presence of lithic and faunal remains, only some long bones present signs of anthropogenic bone breakage (Pineda et al., 2015). The bone surfaces at La Mina are altered because of the leaching of soluble elements from the sediments (Pineda et al., 2014), potentially explaining the absence of cut marks (Pineda et al., 2017b). LM's unit II has been interpreted as a context of high competition between hominins and carnivores (Pineda et al., 2017b) due to the availability of resources, mainly water, prey, and, in the case of hominins, raw materials for tool manufacturing. The accumulation of lithic and faunal remains does not respond exclusively to the action of a single accumulating agent — perhaps except for hyenas in level II.3 — but is due to the succession of multiple independent events occurring over a prolonged period (Pineda, 2018; Pineda et al., 2015, 2017b).

El Forn

The faunal assemblage of levels 2 and 3 is made up of 306 faunal remains, presenting a wide taxonomic list including *Mammuthus meridionalis*, Megacerini indet, *Dama vallonetensis*, *Equus altidens*, *Bison schoetensacki.*, *Hippopotamus antiquus*, *Stephanorhinus hundsheimensis*, *Ursus deningeri*, and *Castor* sp.(Vallverdú et al., 2014b).

The lithic assemblage consists of 103 pieces made of chert, schist, quartz, quartzite, sandstone, and granite and is composed of complete and fragmented flakes, flake fragments, retouched flakes, choppers and chopper-cores, cores, retouched tools on small cobbles, knapping fragments, percussive material, and hammerstones (Table 1). The highlight of the assemblage is the presence of one LCT, described as a cleaver-like tool, made on a large, massive flake in which with a convex transversal edge configured by means of a single generation of very invasive removals (Mosquera et al., 2016).

EF, like LM, would represent an open-air deposit whose accumulation is a palimpsest resulting from the aggregation of multiple independent events (Rosas et al., 2015). With the exception of level II.2, the ratios of different anatomical parts point to a context of low and moderate competition between carnivores and hominins (Pineda, 2018; Pineda et al., 2017b).

In this work, the sample selection has been adapted according to the characteristics of each locality. Thus, following previous studies (Mosquera et al., 2016; Ollé et al., 2023) in Pit 1, the results of the analysis of the cores and large-shaped tools belonging to level II.2 will be presented. In La Mina, since the excavation is still in progress, the cores and large-shaped tools recovered in unit II will be presented, without distinguishing between the different levels of the unit. In El Forn, the distinction between levels is sometimes complicated, especially between levels 2 and 3 (Mosquera et al., 2016) which is why the results of levels 2, 3, and 4

Table 1 Lithic assemblage from unit II at Barranc de la Boella up to the 2022 season. Distribution of primary technological groups based on raw materials across El Forn, La Mina, and Pit 1. Large-shaped tools: includes large cutting and heavy-duty tools over 100 mm, plus ten artefacts from 70 to 100 mm, all on cobble blanks, since there are choppers (unifacial and bifacial). Small-shaped tools: small-retouched flakes, including five flakes over 70 mm, as they are simple denticulates. (modified from Ollé et al. (2023))

Locality	Percussion material	Cores	Flakes				Small-shaped tools	Large-shaped tools	Total	%(1)
			< 100 mm	**> 100 mm**	**Broken**	**F.F. and fragments**				
Pit 1	**15**	**28**	**187**	**1**	**67**	**97**	**22**	**11**	**428**	**-**
Schist	4	1	6	1	1	5		10(*)	**28**	**6.54**
Granite	3								**3**	**0.70**
Sandstone	4	1							**5**	**1.17**
Lydite	2								**2**	**0.47**
Quartz			5			8			**13**	**3.04**
Quartzite	2		1						**3**	**0.70**
Chert		26	175		66	84	22	1	**374**	**87.38**
%(1)	**3.50**	**6.54**	**43.68**	**0.23**	**15.65**	**22.66**	**5.14**	**2.57**	-	**-**
La Mina	**20**	**21**	**162**	**1**	**51**	**133**	**37**	**10**	**435**	**-**
Limestone			1					1	**2**	**0.46**
Schist	7		2	1	1	2	3	5	**21**	**4.83**
Granite	4	1							**5**	**1.15**
Sandstone	4						1		**5**	**1.15**
Porphyry	1							1	**2**	**0.46**
Quartz	2		5			5			**12**	**2.76**
Quartzite	2	1	1		1			1	**6**	**1.38**
Chert		19	153		49	126	33	2	**382**	**87.82**
%(1)	**4.60**	**5.06**	**37.24**	**0.23**	**11.72**	**30.57**	**8.51**	**2.07**	**-**	**-**
El Forn	**10**	**8**	**46**		**9**	**16**	**7**	**7**	**103**	**-**
Schist	7				1		1	5	**14**	**13.59**
Granite								1	**1**	**0.97**
Sandstone	1								**1**	**0.97**
Quartz	1	1				2			**4**	**3.88**
Quartzite	1							1	**2**	**1.94**
Chert		7	46		8	14	6		**81**	**78.64**
%[a]	**9.71**	**7.77**	**44.66**		**8.74**	**15.53**	**6.80**	**6.80**	**-**	**-**
Total	**45**	**57**	**395**	**2**	**127**	**246**	**66**	**28**	**966**	**-**
%[b]	**4.66**	**5.09**	**40.9**	**0.21**	**13.15**	**25.47**	**6.83**	**2.9**	**-**	**-**

*We have included one artefact without a firmly established stratigraphical context

[a]Percentage for each respective site

[b]Percentage for the entire assemblage

will be present together. This study includes all the material recovered from unit II up to the 2022 archaeological fieldwork.

Methods

Given the dynamic character of the knapping sequences (Andrefsky, 1998; Dibble, 1995; Guilbaud, 1995), core analysis proceeded with a technological reading (Inizan et al., 1999), aimed at comprehending and reconstructing the knapping sequences. This section will detail the methodological steps carried out for the technological study of knapping strategies as well as the attributes selected for the study of cores and core reduction intensity.

3D models of the cores were acquired using the Artec Space Spider 3DScan (with the ArtecStudio v15 software) and the Breuckmann SmartSCAN3D-HE Scanner with a 250-mm field of view (Breuckmann Optocat 2012 R2-2206 software).

Core Technical Attributes

The dimensional attributes have been recorded through the 3D models of each core and large-shaped tool. The maximum dimensions (length, width, and thickness) were measured following the minimal box procedure (Laplace, 1972). In addition, 3D models have been used to quantify the volume (cm^3) and surface area (cm^2) of each object.

The examination of the cores initially involved identifying the raw material group and the type of blank used, distinguishing between blanks on flakes and the other types of blanks based on morphological and dimensional criteria. Thus, according to the blank size for some raw materials with a rounded or subrounded morphology such as schist, quartzite, and sandstone, we have used the categories of pebble (diameter < 64 mm), cobble (64–256 mm), and boulder (> 256 mm).

For chert, we have distinguished between nodule (i.e. rounded or subrounded cobbles), block, slab, and angular gravel or chunk according to blank morphology. Slab was used for flat and relatively thin blanks, with a tabular or rectangular shape, so it naturally tends to have angles close to 90º. Nodules are not size specific, with a shape that tends to be rounded to sub-rounded. Angular fragments or chunks are portion or pieces of rock that have separated or fragmented from a larger rock mass (such as blocks, nodules…) with an irregular and angular shape and can be the result of both knapping activities and geological processes. Block was used to define large pieces of rock, with flat surfaces on each side and cubic morphology.

For the technological analysis of the cores, *the number of modified surfaces* has been counted — regardless of whether the objective is flaking or surface preparation- to document unifacial (1 surface), bifacial (2 surfaces), trifacial (3 surfaces), and multifacial (4 or more surfaces) cores.

In addition, *the spatial relationship of the flaking surfaces* has been analysed, distinguishing between contiguous (two adjacent surfaces separated by an edge or a change of plane), opposite (two surfaces located in opposite sectors of the core) and mixed (when there is a combination of contiguous and opposite surfaces).

The *number of surfaces used as percussion platform* has been quantified by distinguishing between unipolar (one percussion surface), bipolar (two surfaces), and multipolar (three or more surfaces). In those cores that have at least two percussion platforms, the spatial relationship between percussion surfaces has been described, distinguishing between contiguous (two adjacent surfaces), opposite (two opposite surfaces), mixed (when there is a combination of adjacent and opposite faces), and peripheral/perimetral (when platforms are articulated around the core perimeter (as, for example, in centripetal strategies) (Carbonell et al., 1983, 1992; Lombao, 2021; Rodríguez-Álvarez, 2004).

To analyse the *volumetric organization of the core reduction sequence*, we have analysed the polarity relationship between all the exploitation series documented in each core, distinguishing between:

- *Longitudinal unipolar*: The removals are conducted from the same percussion platform following the same exploitation axis.
- *Opposing bipolar*: The removals are conducted from two opposite percussion platforms and with an opposite directionality.
- *Orthogonal bipolar*: The removals are performed from two adjacent percussion platforms following perpendicular exploitation axes.
- *Multipolar centripetal*: Removals follow axes oriented to the centre of the exploitation surface.
- *Orthogonal multipolar*: Removals are carried out from at least three different percussion platforms following perpendicular exploitation axes.
- *Multidirectional multipolar*: Cores that present removals in at least three different surfaces, whose scars do not present a clear order.
- *Others/indeterminate*: Corresponds to those cases in which it is not possible to identify a clear strategy, either because of preservation conditions or because the knapping is not sufficiently developed to be able to identify strategies clearly.

Following previous studies (Lombao, 2021; Lombao et al., 2023c; Vaquero, 1999), this analysis has been carried out at two levels: At a general level, we studied the whole core as an analytical unit, and on an elementary level, we analysed each of the core surfaces individually. Core fragments were excluded from the analysis since they do not represent the overall volumetric management of the knapping process.

Based on the number of flaked surfaces, the spatial relationship of the surfaces, the number of percussion surfaces, the spatial relationship of the percussion surfaces, and the arrangement of the scars, different volumetric structures of exploitation were established (VSE) (Lombao et al., 2023c). Furthermore, the relationship between different VSE has been explored by reconstructing the operatory field (Guilbaud, 1995) by analysing the similarities and differences of the different VSE.

In addition to these parameters, we have considered other quantitative attributes such as the scar pattern index (SPI), proposed by Clarkson and colleagues (Clarkson et al., 2006), by computing the vectors established by the initial and final coordinates of each removal. SPI values, ranging from 0 to 1, were obtained by dividing the norm of the vector resulting from the addition of all the vectors, by the sum of the norms of all the vectors (Bretzke & Conard, 2012; Clarkson et al., 2006).

Reduction Intensity

To evaluate the reduction intensity of cores and large-shaped tools from the three localities, we followed the workflow proposed in Lombao et al. (2023b) in which the use and combination of different reduction methods is advocated, to try to overcome limitations that may affect the results such as the type of knapping strategies or the blank size, among others (Lombao et al., 2019). Therefore, in this study, we have combined the use of the volumetric reconstruction method (Lombao et al., 2020), used not only in mode 1 assemblages such as Gran Dolina-TD6.2 (Spain) and Ewass Oldupa (Tanzania) (Cueva-Temprana et al., 2022; Lombao et al., 2023c), but also in more recent periods (Lombao et al., 2023a), the scar density index (Clarkson, 2013; Groucutt et al., 2015; Shipton & Clarkson, 2015a, 2015b), as well as the percentage of non-cortical surface, used elsewhere as a reduction intensity proxy (Douglass et al., 2018; Li et al., 2015).

The volumetric reconstruction method (VRM) (Lombao et al., 2020) is designed to estimate the original volume of cores to calculate the percentage of extracted volume in each core. The technical analysis of the cores was utilized to determine the number of flaking generations on the core's maximum morphometric axes, to establish the corrections needed for each maximum dimension. The number of flaking generations was identified along the maximum length and width, and this number multiplied by the mean platform thickness from the assemblage's flakes was added to the corresponding dimension. For the maximum thickness, the mean flake thickness was used. The median was employed instead of the mean when the distribution of the measured flake thickness or platform thickness was non-normal. Ultimately, the revised dimensions of each core were employed to calculate the ellipsoid volume formula, enabling the estimation of the original blank's volume (see Supplementary Figure S1).

Posteriorly, the volume obtained through 3D core models was divided by the estimated volume of the original blank. This result was then multiplied by 100 to obtain the percentage of remaining volume. Subsequently, the percentage of extracted volume was determined by subtracting this value from 100. Volume (cm^3) was selected as the preferred measurement unit over mass to prevent discrepancies arising from variations in the densities of different raw materials.

The non-cortical surface percentage is calculated by dividing the non-cortical surface area by the total surface area of each core. This calculation is based on the underlying assumption that as reduction advances, the quantity of cortical surface diminishes (Li et al., 2015). The measurement of cortical and non-cortical surface areas has been conducted using the 3D models of the cores, as it enables higher precision (Lin et al., 2010).

The scar density index (SDI) relies on the proportional rise in flake scar density concerning the core's surface area (size), which diminishes as reduction progresses. Thus, this index is founded on the correlation between the count of flake scars larger than 10 mm on a core and its surface area (cm^2), serving as an approximation for reduction intensity (Clarkson, 2013).

Statistical Procedures

Statistical analyses were conducted to investigate three primary aspects: (1) raw material management and blank selection, (2) knapping strategies, and (3) reduction intensity across three localities (see Table 2).

Table 2 Statistical test used in the different analyses of this work

Statistical test	Purpose of use	References
Chi-square	Examine differences in the frequency of technological categories by raw materials	Pearson (1900)
Shapiro–Wilk (S-W)	Assess the normal distribution of the data	Shapiro and Wilk (1965)
Mann–Whitney *U* (M-W)	Assess differences in raw material selection based on blank size and technological categories (two groups)	Mann and Whitney (1947)
Kolmogorov–Smirnov (K-S)	Observe the degree of variability in selected blank volumes, core volumes at discard phase, and percentage of extracted volume	Massey (1951)
Pearson R (r)	Evaluate the linear correlation between the scar pattern index (SPI) and various parameters such as the percentage of non-cortical surface area or the estimated original volume of cores. Also used to assess the agreement between different reduction intensity proxies, assuming normally distributed data	Pearson (1896)
Spearman Rho (r_s)	Evaluate the monotonic correlation between the scar pattern index (SPI) and various parameters such as the percentage of non-cortical surface area or the estimated original volume of cores. Also used to assess the agreement between different reduction intensity proxies, used when data do not meet the assumptions required for Pearson correlation	Spearman (1904)

All statistical analysis was performed in R (R Core Team, 2022), and the R Markdown is openly accessible on Zenodo (Lombao et al., 2024). References to the R packages and versions used and descriptions are available in the Supplementary Material (see Supplementary Information: R Packages in Supplementary Material).

Results

Raw Material Management

The El Barranc de la Boella lithic assemblages are made from diverse raw materials that can be divided into eight different varieties: chert, sandstone, schist, quartz, quartzite, porphyry, granite, and limestone. All of these raw materials are locally available within the quaternary deposits of the El Barranc de la Boella landscape, with distances of less than 5 km from the localities (Mosquera et al., 2016).

The three localities exhibit a similar composition of lithic assemblages (Fig. 2), in which a clear differential management of the different lithologies can be observed. This pattern is characterized by the use of chert to produce flakes and small/medium retouched tools, mainly notches and denticulates (Mosquera et al., 2016; Ollé et al., 2023), and schist for large flake and large-shaped tool production, such as unifacial and bifacial choppers.

At P1, chert is the predominant raw material, accounting for 92.6% of cores and 87.38% of the total lithic assemblage. Smaller flakes and knapping fragments also are made in chert, with all small-retouched tools produced from this raw material demonstrating its primary use in flake production. Nodules or fragments are the blanks used in the 70.9% of the cores, in contrast to 16.66% of cores on flakes.

Schist, though minimally represented in the overall assemblage (6.6%), is the main material for large-shaped tools (83.33%). In this case, 73.73% of large-shaped tools are configured from cobbles and slabs, while 27.27% are made

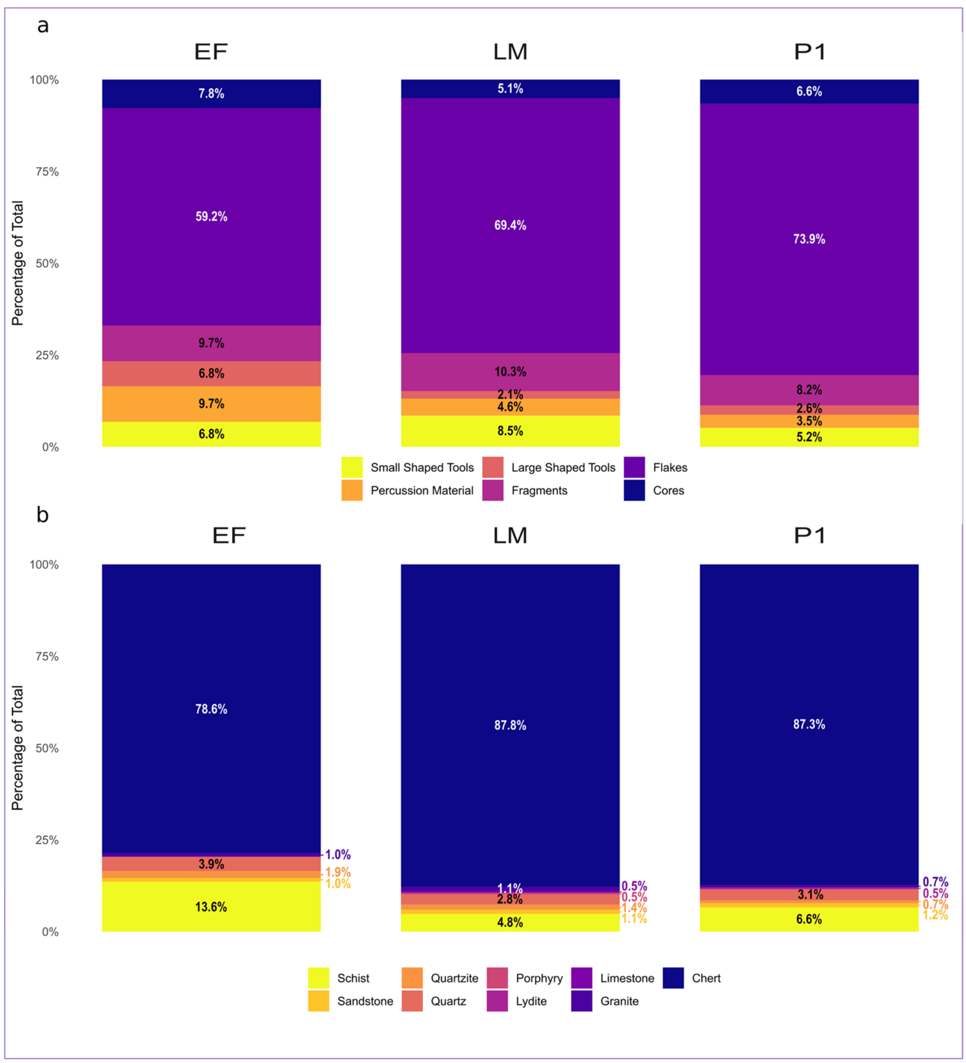

Fig. 2 **a** Composition of lithic assemblage according to technological category in each locality. **b** Composition of lithic assemblage according to raw material in each locality

from flakes (Supplementary Table S1). Lastly, percussion materials consist primarily of schist, along with other raw materials (granite, sandstone, and lydite) that have limited representation in the assemblage (Table 1). This association between raw materials and technological categories is significant ($\chi^2 = 445.52$, df = 30, $p < 0.001$). Nodules and cobbles are primarily used as blanks for cores and large-shaped tools respectively, with cores on nodules showing high variability in volume (Supplementary Table S2).

At LM, while chert remains the main raw material in flake production (90.5%), the composition of large-shaped tools diversifies, with 50% made from schist and smaller proportions from quartzite, porphyry, and chert, with a significant correspondence between lithologies and technological categories ($\chi^2 = 341.48$, df = 35, p-value < 0.001). This locality shows no cores produced on flakes (Supplementary Table S1), and large-shaped tools present considerably higher volumes and dimensions compared to cores (Supplementary Table S3), which are notably smaller but exhibit greater variability (M-W: $W = 9$, $p < 0.001$; K-S: $D = 0.93$, $p < 0.001$).

At EF, unit II features a total of 8 cores, with 87.5% made from chert nodules and the remainder from a quartz cobble. Large-shaped tools are primarily made from schist (60%), with others from quartzite and granite. Again, there is a significant association between raw materials and technological categories in the assemblage ($\chi^2 = 111.62$, df = 25, p-value < 0.001). Volumes at discard and estimated volumes of cores and large-shaped tools show some outliers with very high volumes, yet the general volume trend is similar across both categories (Supplementary Table S4), with schist demonstrating higher estimated volumes compared to chert.

In the three localities, this specialized raw material management becomes evident right from the stage of raw material acquisition. According to the estimates volumes through VRM, blanks selected to produce picks and cleavers are generally larger and more uniform compared to those chosen to produce small- and medium-sized flakes (Supplementary Table S5). The variation in sizes of different lithologies does not appear to be solely dependent on the availability of blanks in the environment. Evidence from the presence of large chert cores in EF and a pick made from a large chert slab in P1, along with the natural nodules found at the site and its surroundings, suggests that chert was also available in relatively large-sized formats. Moreover, volume estimates from the VRM indicate some overlapping volumes for chert and schist in certain cases (Supplementary Table S6).

Core Knapping Strategies

Regarding knapping strategies (see Supplementary Tables S7-10 for quantitative data of flaking and percussion surfaces, orientation of removals, and prepared percussion surfaces), we can find up to eight different volumetric structures of exploitation (VSE), in addition to those cores that are in early or final stages of reduction sequences, and therefore, it is not possible to define a specific VSE. The VSEs are described below.

Initial Cores (VSE A-B Initial)

Four cores recovered in initial reduction stages do not display a defined VSE, as the number of removals on the core surface is low (< 4 scars). However, there are some differences between localities. At P1, these cores are made from nodules, fragments, and flakes (Fig. 3a, b). At LM, all three cores analysed were knapped from irregular chert fragments or nodules on small-size blanks, featuring a maximum of two scars on their surfaces. This indicates sporadic flake production and suggests that any blank can be knapped, regardless of its productive potential. In contrast, at EF, two cores in early reduction stages were identified: One is a chert nodule and the other a quartz cobble (Fig. 5a), both large but with very few detachments, likely discarded due to internal fissures and impurities.

Unifacial Unipolar Longitudinal (VSE A and VSE B)

In these cores, a single surface is exploited following unipolar longitudinal removals that are parallel to each other. We have identified two modalities depending on whether one of the narrow surfaces (VSE A) or one of the broad surfaces of the core (VSE B) is flaked.

In VSE A, the platforms are not prepared; instead, cortical surfaces are used directly as percussion platforms, such as at LM (Fig. 4e) and EF (Fig. 5b), or the ventral surface in the case of core on flakes, as at P1. In these latter cases, there is a marked peripheral development since it covers at least 50% of the perimeter in both cases and using the ventral surface directly as a percussion platform (Fig. 3f).

In the VSE B cores, the platforms are also not prepared, using either cortical or natural non-cortical surfaces as percussion platforms, such as in the cores from EF (Fig. 5c, e). In none of these cases is there a pronounced peripheral development of exploitation; instead, it is concentrated in only a specific sector of the core.

Unifacial Bipolar Orthogonal/Opposite (VSE C)

This type of VSE features a single flaked surface that can be either broad or narrow, using two percussion platforms that may be contiguous or opposite sides of the core, resulting in orthogonal or opposite arrangements of the removals.

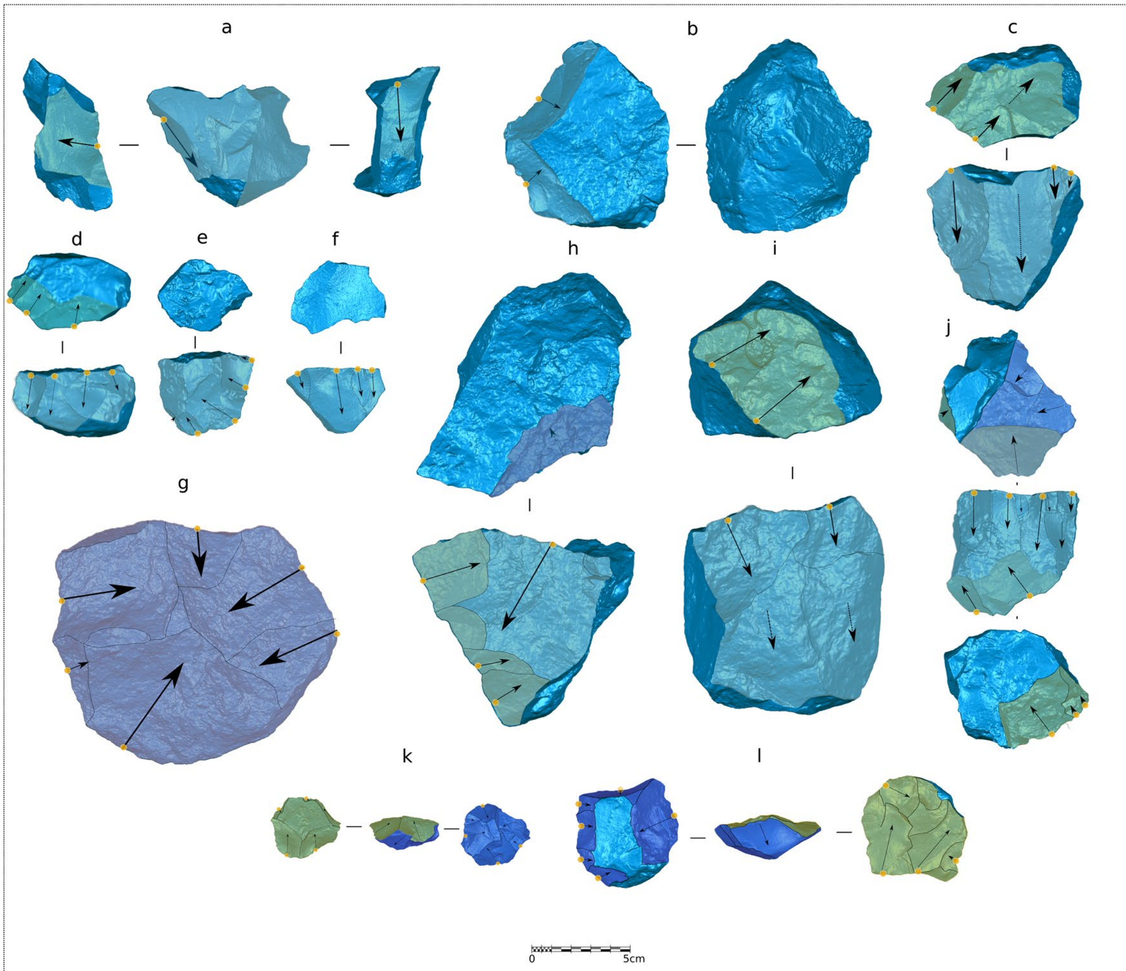

Fig. 3 Cores from Pit 1 unit II.2: **a** BB07 II.2 N13 199 — chert; **b** BB20 II.2 L08 3 — chert; **c** BB15 II.2 L14 1 — chert; **d** BB20 II.2 L07 2 — chert; **e** BB19 II.2 S06 1 — chert; **f** BB18 II.2 Q14 5 — chert; **g** BB07 II.2 O12 72 — sandstone; **h** BB20 II.2 K07 1 — chert; **i** BB17 II.2 J14 1 — chert; **j** BB18 II.2 M11 1 — chert; **k** BB21 II.2 R12 1 — chert; **l** BB22 II.2 A13 1 — chert

In some cases, there is some degree of platform preparation, as at P1, where a flaking surface is first used with two longitudinal unipolar removals from a previously prepared percussion platform; subsequently, the core is rotated, and another series of longitudinal unipolar removals opposite to the first series are carried out (Fig. 3h). However, in this type of VSE, the most frequent practice is the use of unprepared surfaces, either using two adjacent or opposite cortical surfaces, where the detachments are made directly from two opposite cortical platforms (Fig. 4d). The other core is also reduced following bipolar opposite detachments on one of the broad surfaces of the core by using two adjacent non-cortical surfaces as percussion platforms (Fig. 5d, (Fig. 5g). In some cores, there is no overlap between the scars, making it impossible to determine whether an orthogonal or bipolar opposite series occurred, or if they represent two independent unipolar longitudinal series.

Unifacial Multipolar Centripetal (VSE D)

Only a single core within this structure has been identified, consisting of a single flaking surface core with few centripetal removals arranged around the perimeter and covering the entire surface using cortical surfaces as the percussion platform (Fig. 3g). However, considering the size of the blank and the type of raw material used (sandstone), we differentiate it from the bifacial multipolar centripetal cores (VSE H).

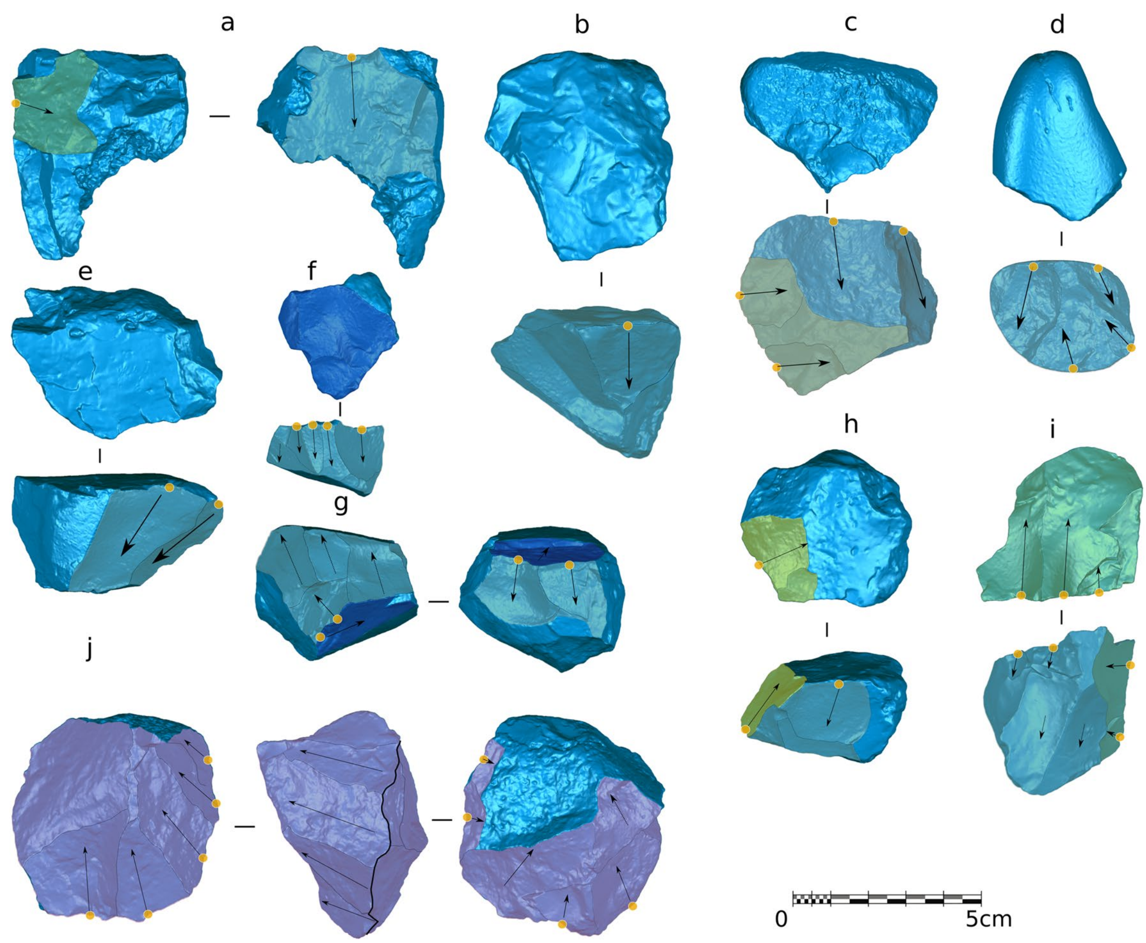

Fig. 4 Cores from La Mina unit II: **a** BB09 II.2 P15 11 — chert; **b** BB16 II.4 W14 1 — chert; **c** BB15 II.3 W14 3 — chert; **d** BB16 II.4 Q16 2 — quartzite; **e** BB16 II.4 Y14 1 — chert; **f** BB14 II.3 W15 6 — chert; **g** BB13 II.2 V14 1 — chert; **h** BB15 II.3 X13 14 — chert; **i** BB16 II.4 X14 9 — chert; **j** BB16 II.1 F17 5 — chert

Bifacial Bipolar-Multipolar Orthogonal (VSE F)

This type of VSE is the most prevalent both at P1 and LM (Table 3). From a technical point of view, they are bifacial since two contiguous or adjacent surfaces of the blanks are flaked by longitudinal unipolar series on each surface with a general orthogonal scar pattern.

At P1, the first surface of the core is modified by detaching small flakes to adapt this surface as a percussion platform for removing deeper flakes on the second surface (Fig. 3c, d, i). At LM, generally, two adjacent surfaces are flaked, either through longitudinal unipolar series alternating the role of both faces as a percussion platform and flaking surface throughout the sequence (Fig. 4h) or through independent longitudinal unipolar series. In one case, these removals are oriented opposite each other and are located on opposite sectors of the core. In this case, both percussion platforms are prepared through marginal removals (Fig. 4f). In other cases, one surface is prepared with orthogonal removals to be later used as a percussion platform of an adjacent flaking surface following unipolar longitudinal knapping strategies (Fig. 4j).

At EF, there is one core that involves two contiguous surfaces, one of them aimed at preparing the percussion platform. There is a dominant longitudinal unipolar trend on the flaking surface, although at the end of the sequence, two marginal detachments were made from an adjacent platform, giving it an orthogonal character (Fig. 5f).

Bifacial Multipolar Centripetal (VSE H)

In this type of cores, two opposing broad surfaces separated by an intersection plane are knapped. The removals are articulated along the perimeter of the core, converging at its centre. Only three examples of this type of exploitation have been recovered.

At P1, there are two centripetal bifacial cores, although they have very different morphologies. In one case, removals have a secant angular relationship with respect to the intervention plane and form a sinuous edge, giving it a

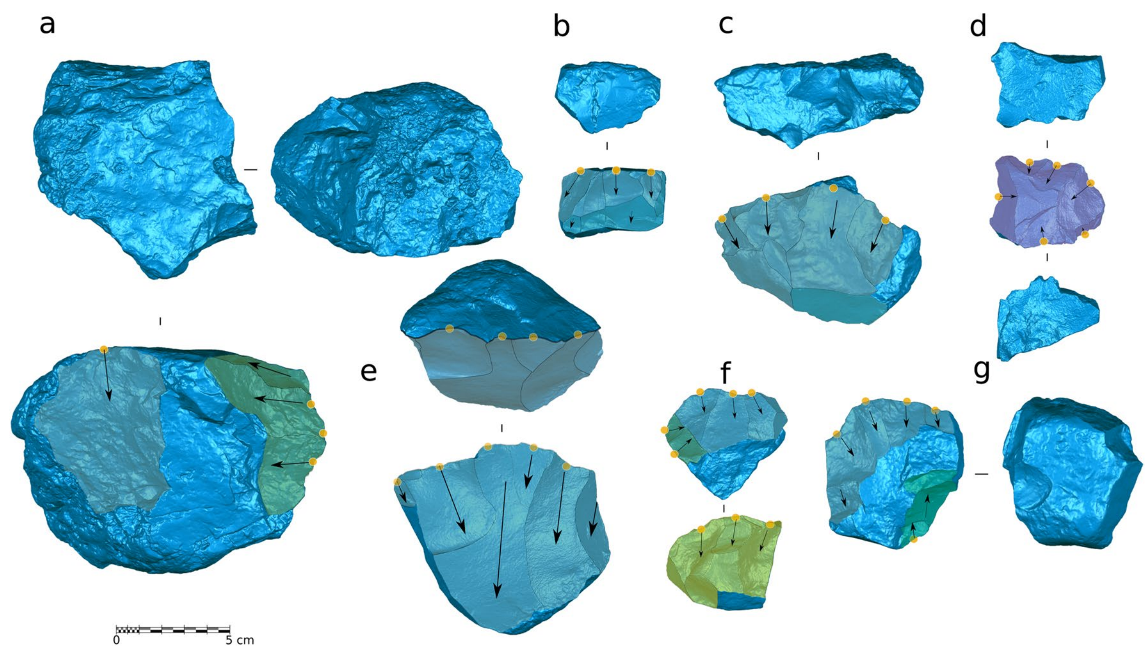

Fig. 5 Cores from La El Forn unit II: **a** BB13 II.2 D12 1 — chert; **b** BB13 II.2 H13 4 — chert; **c** BB12 II.3 I14 9 — chert; **d** BB11 II.2 J13 4 — chert; **e** BB13 II.2 O15 1 — chert; **f** BB13 II.2 Q14 1 — chert; **g** BB12 II.3 I10 2— chert

Table 3 Frequency of volumetric structures of exploitation according to El Barranc de la Boella localities. EF, El Forn; LM, La Mina; P1, Pit 1

VSE	EF	LM	P1	Total
A-B initial	2 (25%)	3 (20%)	4 (16.7%)	**9 (19.1%)**
A	1 (12.5%)	1 (6.7%)	2 (8.3%)	**4 (8.5%)**
B	2 (25%)	0 (0%)	1 (4.2%)	**3 (6.4%)**
C	2 (25%)	2 (13.3%)	1 (4.2%)	**5 (10.6%)**
D	0 (0%)	0 (0%)	1 (4.2%)	**1 (2.1%)**
F	1 (12.5%)	5 (33.3%)	8 (33.3%)	**14 (29.8%)**
H	0 (0%)	1 (6.7%)	2 (8.3%)	**3 (6.4%)**
I	0 (0%)	2 (13.3%)	2 (8.3%)	**4 (8.5%)**
J	0 (0%)	0 (0%)	1 (4.2%)	**1 (2.1%)**
Others	0 (0%)	1 (6.7%)	2 (8.3%)	**3 (6.4%)**
Total	**8 (17%)**	**15 (31.9%)**	**24 (51.1%)**	**47 (100%)**

discoid morphology (Fig. 3k). In the second case, it is a bifacial core with a flatter preferential surface while the second surface has a more convex morphology and scar removals with wider angles (Fig. 3l).

VSE H core from LM shows two flaking opposing surfaces separated by an intersection plane. On one surface, removals articulate along the perimeter of the core, converging at its centre. Conversely, on the opposite surface, the removals follow a unipolar longitudinal pattern without fully altering the core's perimeter (Fig. 4i).

Trifacial/Multifacial Multipolar Orthogonal/Multidirectional (VSE I)

There are two cores within this VSE; the first case is technically an orthogonal trifacial core that has been obtained by two longitudinal series performed on the same surface from two opposite platforms both with preparation removals. The removals series are carried out on one of the wide faces of the core and have marked development along its perimeter following a volumetric concept similar to VSE B (Fig. 3j). The other core corresponds to a multifacial multipolar core made on chert with an angular shape (polyhedron-like) in which flake removals follow multiple directions.

Bipolar-on-Anvil Cores (VSE J)

This group represents a core that has been reduced only using the bipolar-on-anvil technique. A large removal is first carried out to prepare the percussion platform and covers the entire surface. Subsequently, the core is reduced following the bipolar-on-anvil technique, changing the percussion platform throughout the sequence by means of rotations but maintaining the same flaking surface (Fig. 3e). It is distinguished from the "Others" group because in this case, the application of this technique does not appear to be due to the small size of the cores.

Others

This group corresponds to small-sized multifacial cores in a final reduction stage, either due to a high degree of depletion resulting from increased reduction intensity or the use of small blanks. It is precisely this high degree of depletion that complicates the recognition of the knapping strategy applied during the reduction sequence, although given their size, it is not ruled out that the bipolar technique on anvil or a combination of freehand-bipolar on anvil was employed during the reduction sequence of one of them. This kind of exploitation seems to be a strategy aimed at maximizing blank utilization more than a specific knapping strategy itself.

Reduction Intensity and Volumetric Depletion

Across all localities, it is consistently observed that large-shaped tools exhibit significantly lower reduction intensity compared to cores. Specifically, at P1 and LM, large-shaped tools demonstrate a notably lower reduction intensity than cores, reflected by the percentage of extracted volume (Fig. 6), SDI, and percentage of non-cortical surface (see Supplementary Tables S11-S13).

At P1, reduction intensity remains consistently low across different technological categories, raw materials, or VSE, with cores frequently reduced by 20 to 70% of their original volume, with only one exception exceeding this range (see Supplementary Table S11).

There is no significant correlation between the percentage of volume extracted in cores and the estimated original volume of the blanks (Spearman $r_s = -0.59$, $p = 0.02$), suggesting that the reduction intensity is somewhat independent of the blank's size. However, a very strong correlation exists between the estimated and the discarded volume of cores (Spearman $r_s = 0.95$, $p < 0.001$), likely due to the low reduction intensity seen overall.

Furthermore, there is no statistically significant correlation between the scar pattern intensity (SPI) and the percentage of volume extracted from cores (Pearson $r = -0.34$, $r^2 = 0.11$, $p = 0.21$), meaning that more intense reduction does not necessarily result in more complex scar patterns, nor are these patterns influenced by the original size of the blanks (Spearman $r_s = -0.01$, $p = 0.95$).

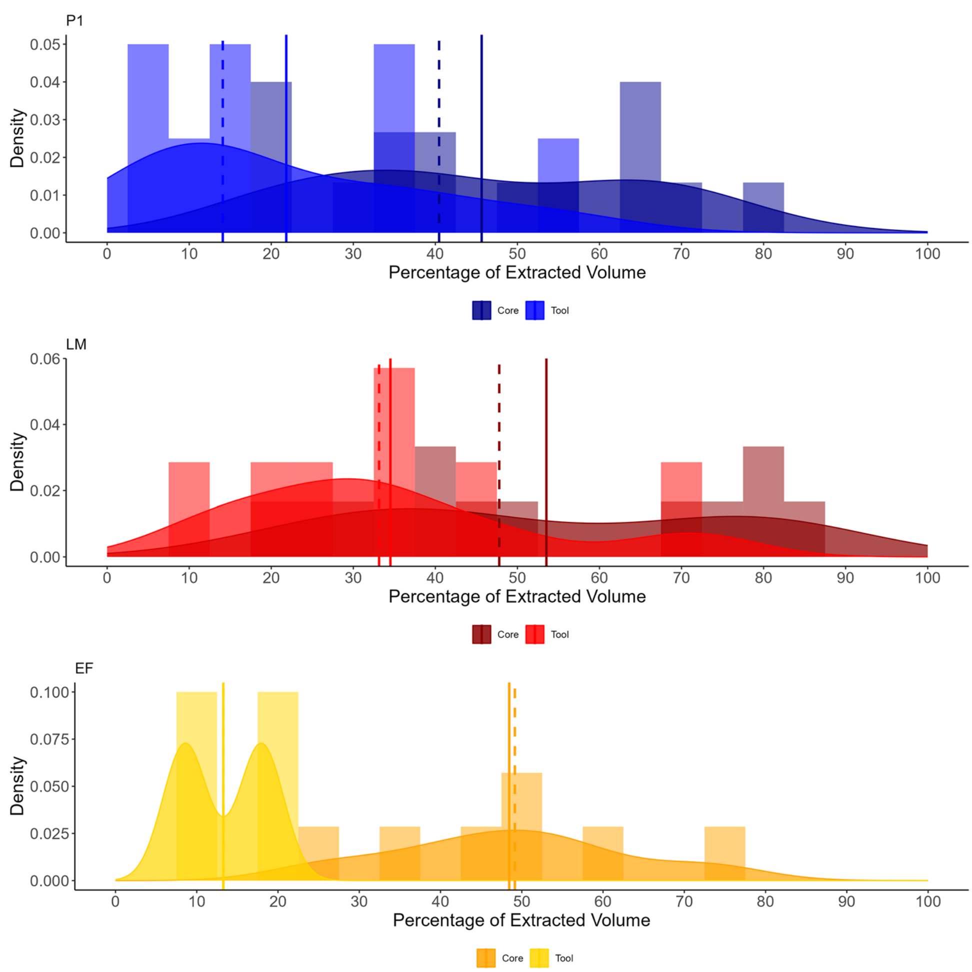

Fig. 6 Histogram and density line of the percentage of extracted volume for cores and large-shaped tools by locality. The solid line indicates the mean, and the dashed line represents the median

In contrast, large-shaped tools show a distinctly lower reduction intensity compared to cores, as evidenced by their percentage of volume extracted and confirmed through a Mann–Whitney test (M-W: $W = 102$, $p = 0.005$). This lower reduction intensity is consistent with findings from the SDI and the percentage of non-cortical surface, which are lower for large-shaped tools (see Supplementary Tables S10 and S11). Notably, there is a strong positive correlation between the original volume of blanks and their reduction intensity (Pearson $r = 0.92$, $r^2 = 0.84$, $p = 0.001$), indicating that larger blanks tend to have higher reduction intensities.

Moreover, a strong negative correlation between SPI and the percentage of volume extracted (Pearson $r = -0.84$, $r^2 = 0.71$, $p = 0.008$) suggests that as reduction increases, large-shaped tools develop more complex shaping patterns. Similarly, a negative correlation exists between SPI and estimated volume (Pearson $r = -0.79$, $r^2 = 0.63$, $p = 0.01$), indicating that larger blanks generally undergo simpler shaping processes.

At LM, cores have a higher average reduction intensity compared to large-shaped tools — 53.5% versus 34.5%, respectively (Supplementary Table S11). This disparity is further highlighted by SDI and non-cortical percentages (Supplementary Tables S12 and S13). A stronger correlation exists between the degree of depletion (i.e. volume) and reduction intensity in cores (Pearson $r = -0.70$, $r^2 = 0.50$, $p = 0.01$) than in large-shaped tools (Spearman $r_s = -0.67$, $p = 0.25$), with cores showing greater volumetric depletion.

No significant correlations are found between SPI and percentage of extracted volume, or between SPI and original blank size in either cores or large-shaped tools, indicating that flaking patterns do not systematically change as reduction progresses (cores: Pearson $r = -0.44$, $r^2 = 0.19$, $p = 0.16$; large-shaped tools: Spearman $r_s = 0.28$, $p = 0.5$).

The original volume of the blanks at EF does not seem to play a significant role in the knapping strategies considering the low correlation between SPI and volume estimates (Spearman $r_s = 0.03$, $p = 0.96$) and the statistical insignificance between the original volume of the blanks and percentage of extracted volume (Spearman $r_s = 0.67$, $p = 0.1$).

At EF, the three proxies used to estimate reduction intensity indicate a pattern similar to LM and P1. Thus, the percentage of non-cortical surface, the percentage of extracted volume, and the SDI indicate that large-shaped tools have lower values compared to cores, indicating a lower overall reduction intensity (Supplementary Tables S11-S13).

However, the low degree of correlation between the SPI and the variables used to estimate reduction in cores (percentage of non-cortical surface: Pearson $r = 0.13$, $r^2 = 0.01$, $p = 0.77$; SDI: Pearson $r = -0.20$, $r^2 = 0.04$, $p = 0.65$; and percentage of extracted volume (Pearson $r = 0.10$, $r^2 = 0.01$, $p = 0.8$) indicates that there are no changes in flaking patterns

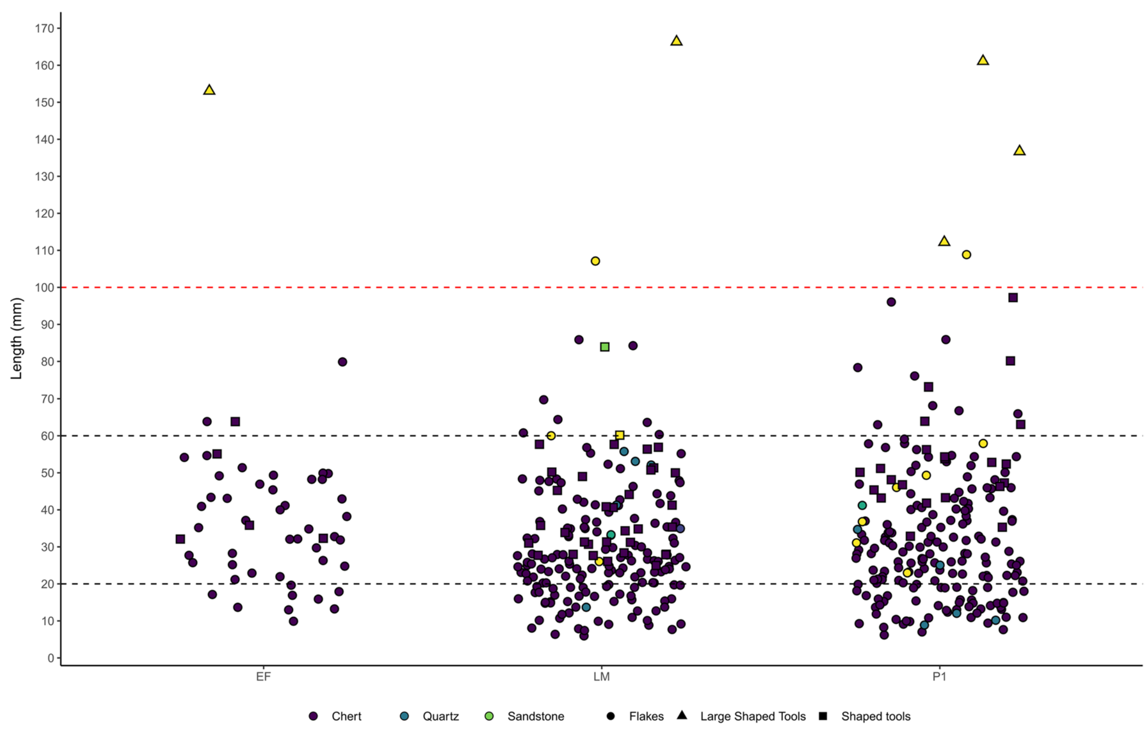

Fig. 7 Jitter plot showing the length (mm) of unretouched flakes, large-shaped tools made on flakes, and small-shaped tools made on flakes by raw material and locality

as reduction progresses, with these patterns remaining relatively constant.

Large Flake Production (> 100 mm)

The production and use of large schist flakes have been documented across all the three localities (Fig. 7). In EF, there is evidence of using a large flake for the production of a cleaver-like tool (Mosquera et al., 2016). P1 features simple flakes larger than 100 mm, including an unretouched flake, a pick, a knife, and a cleaver, while in LM, an unretouched flake and a knife made from a large flake have been documented (Ollé et al., 2023).

Notably, most of the cores recovered from these localities were not large enough to produce such significant schist flakes. The larger cores were typically made from chert. This suggests that the large schist flakes were likely produced elsewhere and then introduced to the sites already shaped.

Spatiotemporal Fragmentation of Reduction Sequences

The limited number of schist flakes recovered at each locality indicates spatiotemporal fragmentation of the procurement, shaping, and use/discard phases of the large-shaped tools (Fig. 8). Additionally, the absence of giant cores (sensu Sharon, 2009), the presence of large flakes (> 100 mm) made from schist (both retouched and unretouched), and the absence of schist flakes from the large-shaped tool shaping phases confirm this spatial–temporal fragmentation of the reduction sequence in this raw material.

Nevertheless, we must be cautious with this interpretation, since given the local availability of raw materials, it cannot be ruled out that the shaping phase occurred concurrently with raw material procurement that may have taken place close to the site but outside our current excavation boundaries. Therefore, the giant cores or the shaping of large tools might have occurred nearby but not within the immediate excavated areas.

Chert shows greater integrity of the reduction sequences, as all the elements of the knapping process have been recovered in the three localities. Furthermore, in P1, the presence of refits and conjoins (Mosquera et al., 2015), along with the spatial association of the remains (Ollé et al., 2023), suggests that knapping took place in situ. In contrast, this has not been documented in EF or LM (Mosquera et al., 2015, 2016). Therefore, differential raw material management can also be observed through the study of the reduction sequences integrity.

Discussion

The three localities exhibit common features: (1) the same procurement pattern of local raw material (< 5 km); (2) differential blank selection pattern according to raw material; (3) differential raw material management in which schist is mainly selected for large flakes and large-shaped tool production and chert for small flake production; (4)

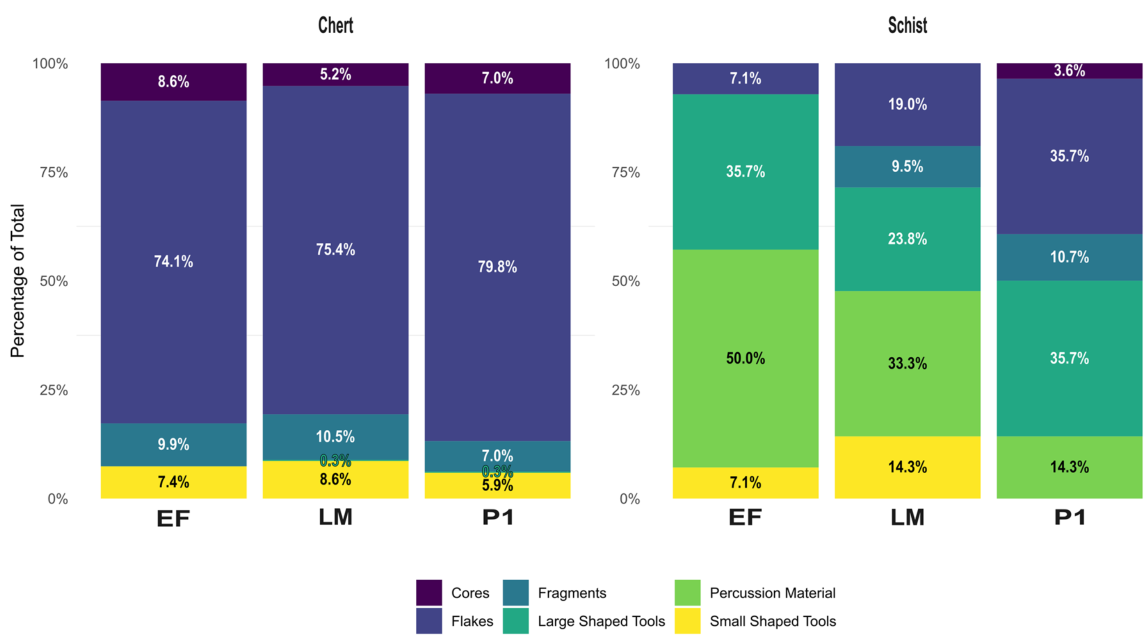

Fig. 8 Distribution of technical categories in chert (left) and schist (right) by locality

an operatory field characterized by longitudinal unipolar knapping strategies, with the presence of more complex core knapping strategies at P1 and LM; (5) the reduction sequences appear to be independent of the volumetric characteristics of the blanks in the case of core knapping strategies but not for large shape production, in which blanks with morphologies and volumes more conducive to the production of large-shaped tools such as picks are intentionally selected; (6) the production of large flakes in schist; (7) the differential transport pattern, reflected in the fragmentation of reduction sequences in schist, and the complete reduction sequences in chert. To these similarities, we can add those related to (8) assemblage composition and (9) main typologies of large-shaped tools (Ollé et al., 2023), as well as (10) a similar use of the environment, with the particularity of the "snapshot" butchering site of P1 (Mosquera et al., 2015; Pineda et al., 2017b).

All three localities at El Barranc de la Boella (BB) present an operatory field in which predominantly utilize longitudinal unipolar schemes. The VSEs can either be maintained throughout or represent different stages within the same reduction sequence, depending on the presence of removals aimed at preparing platforms and the number of flaking surfaces. Thus, unipolar unifacial cores or orthogonal and opposing bipolar unifacial cores can evolve into bifacial cores with more complex knapping systems (Fig. 9). The core knapping strategies are not influenced by raw material constraints, nor by the size or morphology of the blank, as there are no changes in flaking patterns (scar pattern index) as reduction progresses, and there is no clear relationship between SPI and the estimated volume of the cores in any of the three localities. Additionally, there is no correlation between estimated volume and the percentage of extracted volume. This suggests that the application of knapping strategies is independent of these external factors.

A considerable portion of the bifacial cores fit within the framework of the unipolar longitudinal volumetric concept, as the reduction sequence typically involves working on two adjacent surfaces, each surface being knapped using longitudinal unipolar schemes. The preparation of percussion platforms is minimal and primarily focuses on creating suitable platforms through deep removals.

Some bifacial cores demonstrate complex volumetric management, utilizing previously flaked surfaces as percussion platforms, similar to the *système par surface de débitage alternée* (S.S.D.A.) (Ashton, 1992; Forestier, 1993). This suggests a degree of control over core morphology and a more organized sequence of knapping, although there is no strict hierarchization as the role of the flaked surfaces changes throughout the sequence. The LM locality offers the clearest examples of such cores and shows the highest reduction values.

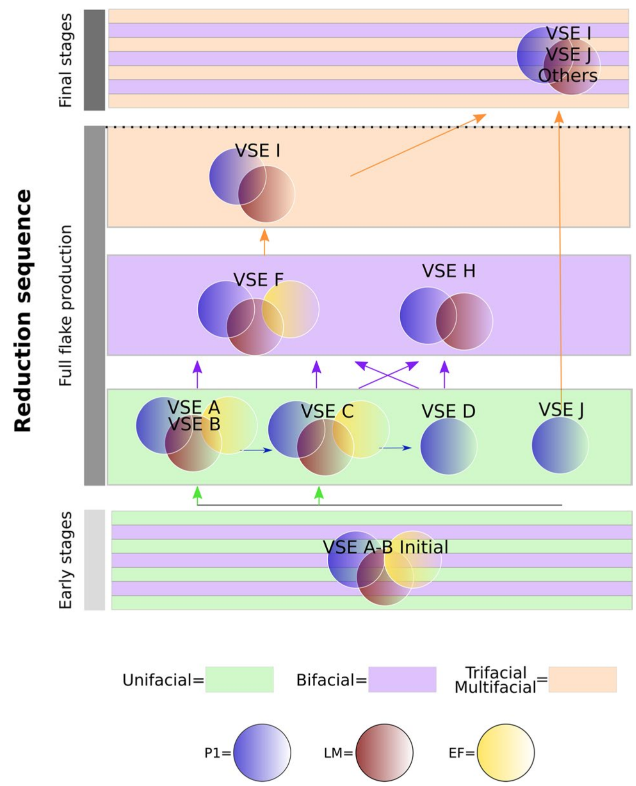

Fig. 9 Reconstruction of the operatory field and the interrelationships of the VSE across the reduction sequence, divided into early stages, full flake production, and final stages. Each circle represents the presence of a specific VSE at each locality (P1, LM, EF). The colour coding within the circles indicates the different localities: The number of flaking surfaces in each VSE is indicated by the rectangles. The arrows illustrate the potential transitions and interrelationships between different VSEs throughout the reduction sequence

This could imply the presence of a procedural template (Chase, 2008; Gowlett, 1984, 1986), i.e. a specific organization of actions that facilitates modifications in the core while preserving angular relationships between surfaces, allowing for extended knapping sequences. However, these cores lack comprehensive volume management, as flaking occurs primarily on one or two surfaces, leaving a significant portion of the volume unmodified. Removals are structured to continue the knapping sequence without the progressive reduction in volume significantly affecting productivity. This may result in a greater number of flakes, but not necessarily greater control over flake morphology.

Although rare, the occurrence of centripetal strategies in the three assemblages is notable, with only four centripetal cores documented. Two of these examples show partial volume management, either due to their unifacial nature (Fig. 3g) or limited perimeter development (Fig. 4j), while two cores at P1 show complete bifacial volumetric management articulated on two broad and opposite surfaces (Fig. 3k, l).

The three assemblages at BB show a presence of cores in initial reduction stages. In EF, these cores are the largest within the assemblage and might be associated with testing raw materials, which are ultimately discarded due to impurities and internal fissures. In P1 and LM, these cores are found on small chert fragments. Additionally, very small or completely exhausted cores have been documented in P1 and LM, indicating higher volumetric depletion than generally inferred for these assemblages and could represent opportunistic strategies linked to enhanced raw material utilization, rather than reflecting specific volumetric organizations.

A clearly different pattern is distinguished for large-shaped tools, which are typically characterized by short knapping sequences focused on specific sections of the blanks (Ollé et al., 2023). Interestingly, in the case of picks, the original blank volumes appear to influence the shaping processes, as larger blanks exhibit lower reduction intensity, a greater amount of cortical surface, and relatively simpler shaping processes.

The large-shaped tools recovered at BB reflect elements of cognitive complexity also observed in the core reduction dynamics, such as the more complex and efficient organization of the actions and the ability to overcome the raw material constraints. On the one hand, because, although generally a single series of removals is identified, it presents numerous invasive removals oriented towards the shaping of a distal trihedron, leaving the base unmodified. In one pick from P1, two long-shaping series have been documented (Mosquera et al., 2016; Ollé et al., 2023). On the other hand, the selection of morphologies more conducive to the shaping of some distally configured picks seems to be governed by the principle of gestural economy (sensu Vaquero, 1997, 1999), which, together with their differential transport (spatiotemporal fragmentation of the reduction sequences), reflects an anticipatory and planned behaviour assumed in other assemblages with similar chronologies (Bourguignon et al., 2016a). Moreover, this criterion of "minimal modification" and specific selection of blanks with specific morphological criteria has been considered by some authors as evidences of some degree of predetermination for later mode 2 assemblages such as La Noira (Moncel et al., 2020a).

In sum, the three localities of BB show a differential reduction sequence patterns according to goal and to raw material (Fig. 10). The existence of a procedural template in the knapping strategies, with the gestural economy in the case of large shape tools productions, suggests a high level of planning and anticipatory capabilities.

"New" Behaviours: A Step Forward in Complexity Compared to the European Mode 1 Assemblages?

Although some localities the mode 1 occupations would have a markedly sporadic character, reflected in the small quantity of lithic assemblages, as is the case of Bois-de-Riquet-US2 (France, 1.3–1.1 Ma) (Bourguignon et al., 2016b), Le Vallonnet (France, 1.2–1.1 Ma) (Cauche, 2009; Michel et al., 2017), Atapuerca-TE9 (Spain, 1.22 Ma) (de Lombera-Hermida et al., 2015) and AtapuercaTD3-4 (Spain,~ 1 Ma) (Carbonell et al., 2024; Ollé et al., 2013), Pakefield (Great Britain,~ 700 ka) (Parfitt et al., 2005), and Happisburgh 3 (Great Britain, 990–700 ka) (Parfitt et al., 2010) making difficult or even impossible to identify long-range behavioural patterns, it is possible to discuss some of the aspects related to the technological behaviour of these human groups (see Table 4).

One of these technological aspects may include the utilization of a wide variety of local raw materials (< 5 km) to produce stone tools as observed in mode 1 assemblages from Dmanisi, Pirro Nord, Barranco León and Fuente Nueva 3, Gran Dolina-TD6, Pont-de-Lavaud, Monte Poggiolo, and others (Arzarello et al., 2016; Baena et al., 2010; Barsky et al., 2015; Carbonell et al., 1999; de Lombera-Hermida et al., 2016; Despriée et al., 2018; Mosquera et al., 2018; Peretto et al., 1998; Toro-Moyano et al., 2011).

In some cases, there may even be variations in the management of raw materials, with the potential explanations varying. In sites like Monte Poggiolo and Pirro Nord, the raw material management can be attributed to the properties of the raw materials, particularly the size of available nodules, which influences the knapping strategies applied (Arzarello et al., 2015, 2016; Carpentieri & Arzarello, 2021; Peretto et al., 1998). In Dmanisi (Georgia), *ca.* 1.8 Ma ago (Lordkipanidze et al., 2007), raw materials were exploited with different intensity levels based on their quality (Baena et al., 2010; Mgeladze et al., 2010). In Gran Dolina-TD6 (960 ± 120 ka) (Duval et al., 2018), which exhibits greater raw material diversity, there is a higher degree of core reduction intensity (Lombao et al., 2023c) and a greater presence of retouched flakes (Mosquera et al., 2018; Terradillos-Bernal & Rodríguez-Álvarez, 2014, 2017) in the higher quality lithologies.

In terms of variability in core knapping strategies, European mode 1 assemblages are typically characterized by the presence of "unstructured" or "expedient" knapping strategies, which rely on unifacial, multifacial, multipolar, and, rarely, centripetal methods. These knapping strategies are often subordinated to the geometric features of the raw materials, reflecting the absence of substantial attention to preserving core volumetric conditions, especially in terms of platform preparation (e.g. Carpentieri & Arzarello, 2021; Lombao et al., 2023c; Mosquera et al., 2018).

Furthermore, European mode 1 assemblages tend to feature short reduction sequences. However, some sites, where these shorter sequences predominate, such as Monte Poggiolo have occasionally shown relatively long reduction sequences, as evidenced by the presence of refits (Arzarello

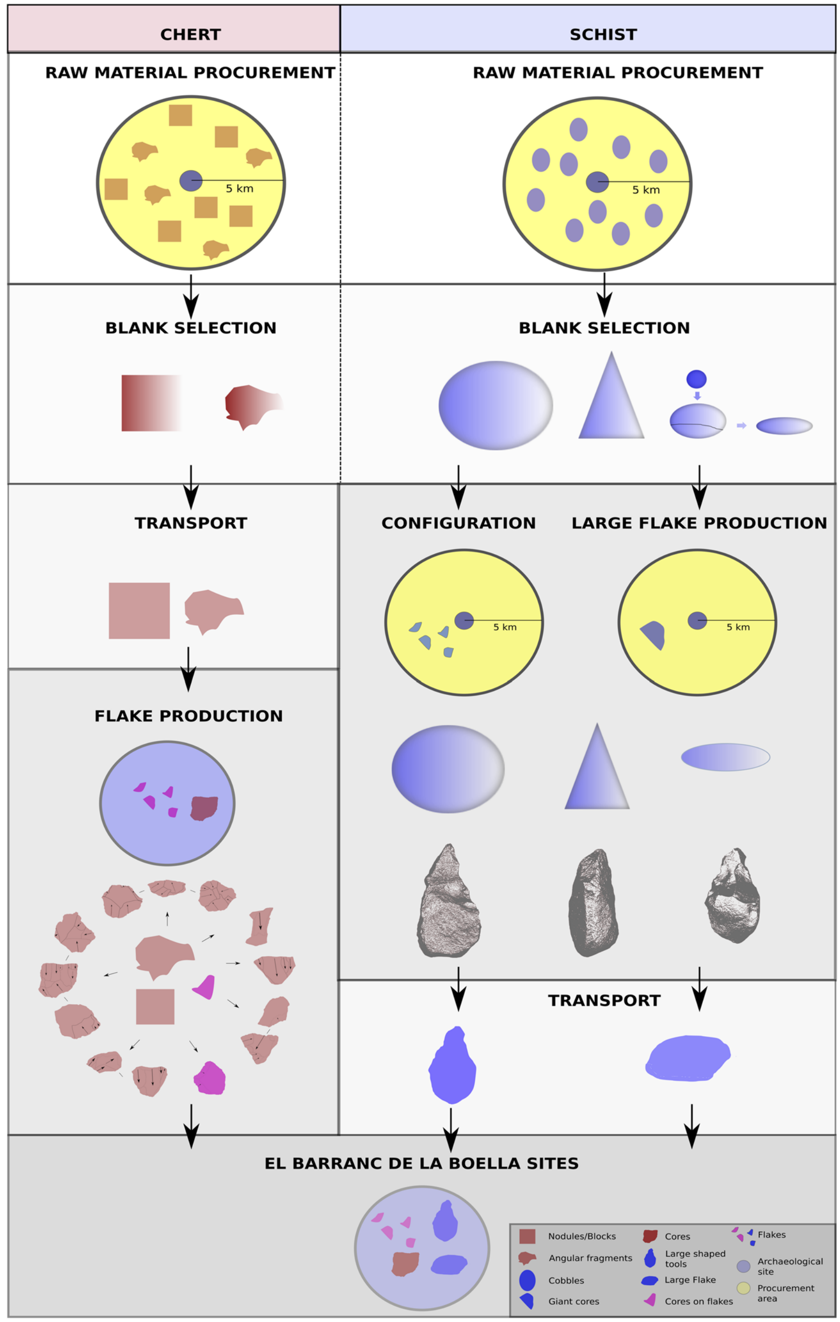

Fig. 10 Reduction sequences of chert and schist for the three BB localities

et al., 2016; Peretto et al., 1998). This would be reflected in a low degree of reduction intensity of the cores and/or in a lower degree of depletion of the volumetric potential of the cores.

This integrity in reduction sequences is observed in some European mode 1 sites. Gran Dolina-TD6.2, Monte Poggiolo, Fuente Nueva 3, and Barranco León exhibit the presence of all elements in the reduction sequences (Arzarello et al., 2016; Barsky et al., 2022; Carbonell et al., 1999; Toro-Moyano et al., 2011; Yravedra et al., 2024). This, along with the presence of refits in some sites such as TD6.2 (Mosquera et al., 2018) and Neogene chert nodules with substantial remaining volumes, suggests a systematic transport of material to the cave for in situ knapping. In some cases, such as Fuente Nueva 3, some larger-sized flakes were introduced into the site and re-knapped expediently (Barsky et al., 2022).

Regarding large flake production, European mode 1 assemblages typically lack large flakes. However, Gran Dolina-TD6.2 stands out as an exception, with some flakes larger than 10 cm recovered (Mosquera et al., 2018). This production may depend on the characteristics of the raw

Table 4 Main technological features of European mode 1 assemblages, late Early Middle Pleistocene mode 2 assemblages, and El Barranc de la Boella localities

	European mode 1	El Barranc de la Boella	Early Middle Pleistocene sites
Raw material selection	Local raw materials (< 5 km)	Local raw materials (< 5 km)	Local raw materials (< 5 km)
Raw material management	Variations in raw material management depending on the size and quality of available nodules	Selective management with a strategic use of different raw materials for specific purposes	Selective management with a strategic use of different raw materials for specific purposes
Knapping strategies	"Unstructured" or "expedient" strategies, dependent on the geometric features of the raw material	More hierarchical and volumetric management of knapping, allowing flexibility with various volumes and shapes, largely independent of raw material constraints	Diverse, including centripetal, bifacial, and orthogonal, largely independent of raw material constraints
Reduction intensity	Low intensity with generally short reduction sequences	Exhibits both low and high reduction sequences	Exhibits both low and high reduction sequences
Large flake production (> 10 cm)	Generally, lack large flakes (except in sites like Gran Dolina-TD6.2) but always used as cores	Intentional production of large flakes and large-shaped tools on flakes	Intentional production of large flakes and large-shaped tools on flakes
Giant cores	Absence	Absence in archaeological context, but presence inferred from the presence of large flakes	Presence in some cases
Integrity of reduction sequences	Presence of complete reduction sequences in some sites, with systematic transport of material for in situ knapping (except in some cases in FN3)	Fragmentation of reduction sequences in the production of large-shaped tools and large flakes, while flake production maintains reduction sequence integrity	Fragmentation of reduction sequences in the production of large-shaped tools and large flakes, while flake production maintains reduction sequence integrity
Large-shaped tool production	–	Mainly picks with limited shaping and cleavers, few heavy tools	Variety of large-shaped tools, including handaxes
Standardization of tools	–	Limited; picks show some standardization	Low to moderate; varies by site and tool type
Symmetry	–	Low to moderate, with limited bifacial symmetry	Varied; often more symmetrical, especially in handaxes

material, as these flakes are produced from Neogene chert, which exists in the form of metric or decametric blocks (García-Antón, 2016). Consequently, the only viable approach to manage this lithology is to produce large flakes or fragments. In contrast to BB, the large flakes in TD6.2 are exclusively intended to be used as blanks for cores and not for shaping large tools.

In sum, there are differences in raw material management, core knapping strategies, reduction intensity, large flake production, integrity of reduction sequences, and the production of large-shaped tools between the BB localities and European mode 1 sites (Table 4). However, some differences are more pronounced than others. For example, much of the variability observed in knapping strategies is common to both, as is the partial management of volume, the predominance of longitudinal unipolar schemes, the presence of orthogonal bifacial/multifacial cores, and the utilization of the bipolar on an anvil technique. However, in mode 1 assemblages, the application of different strategies seems to be a response to the raw materials constrains, whereas in the BB sites, it is independent of these characteristics. Other differences, such as the integrity of reduction sequences and large flake production, are more evident, suggesting a clearly different technological behaviour between BB and European mode 1 assemblages.

"Old" Behaviours: A Step Back in Complexity Compared to the European Early Middle Pleistocene Mode 2 (~ 780–600 ka)?

After evaluating the technological characteristics displayed by the three BB localities and considering the changes and similarities compared to other European mode 1 sites, it is essential to examine the core knapping strategies and tool shaping dynamics in slightly later assemblages (between 800 and 600 ka) to provide a comprehensive context.

A) Core Reduction Sequences

A common trait found in early Middle Pleistocene sites is the selective management of raw materials. For example, at the US4 level of Bois-de-Riquet in France, dating between 780 and 680 ka (Bourguignon et al., 2016a), there is a clear connection between the raw materials used, their size, and the type of tools produced. Basalt is employed for obtaining large flakes and large tools, while quartz is used for producing small flakes, and aplite is chosen for hammerstones and heavy-duty tools (Bourguignon et al., 2016a). Notarchirico in Italian peninsula (695–600 ka) shows the reduction of small-sized flint nodules through unifacial and multifacial strategies, with minimal platform preparation, while other raw materials like quartz, quartzite, or limestone are occasionally used to obtain large flakes for handaxe production (Carpentieri et al., 2023; Moncel et al., 2019, 2020b).

In Stratum a of La Noira (France), dated around 665 ± 55 ka (Despriée et al., 2011, 2017; Moncel et al., 2013, 2020a, 2021), the primary raw material is a tabular silicified limestone found in the vicinity of the site (Moncel & Ashton, 2018). Selection is based on thickness, with thicker pieces used for flake production and those with more acute natural angles chosen for handaxe configuration and more structured knapping strategies for small flakes (Moncel et al., 2020a, 2021). The core reduction dynamics documented at La Noira reveal two main reduction sequences: one for producing small flakes and another for larger ones. The production of small flakes involves multiple strategies depending on the platform type and number, with a prevalence of centripetal bifacial strategies characterized by short series of convergent and invasive removals. In contrast, the larger cores are characterized by disorganized and non-standardized management (Moncel et al., 2020a, 2021).

Large cores intended for large flake production, also known as "giant cores" (sensu Sharon, 2009) have also been identified at the US4 level of Bois-de-Riquet. In both sites, giant cores exhibit partial exploitation, with the natural surfaces of the blank acting as percussion platforms and showing a low degree of reduction and volumetric exhaustion. While the absence of platform facets could indicate good control over morphology and angular relationships between surfaces, this type of management suggests opportunistic behaviour related to blank morphology. However, some authors propose that the selection of the blank itself could indicate anticipatory behaviour (Bourguignon et al., 2016a).

Furthermore, early Middle Pleistocene assemblages exhibit an increased independence from raw material constraints compared to mode 1 assemblages. This is reflected in the growing prevalence of centripetal bifacial cores, allowing for the independent management of the entire volume regardless of the initial blanks' characteristics. Additionally, there is a more deliberate selection of favourable morphologies based on intended knapping strategies. While earlier sites like El Barranc de la Boella or the US4 level of Bois-de-Riquet primarily feature unipolar longitudinal and orthogonal strategies, more recent sites like La Noira introduce complex volumetric management strategies, with discoidal strategies being prominent. These strategies overcome the constraints imposed by raw materials (Gallotti & Peretto, 2015). However, in the case of Notarchirico, core reduction strategies remain stable throughout the stratigraphic sequence, regardless of the presence or absence of handaxes among different layers (Carpentieri et al., 2023; Moncel et al., 2019, 2020b; Santagata et al., 2020).

Other sites, such as Moulin Quignon in Abbeville (France), dating to 672 ± 54 ka (Antoine et al., 2019), show substantial variability in knapping strategies. This variability includes cores reflecting opportunistic strategies, with few removals and rare platform preparation, as well as other cores with more structured strategies, like unifacial and bifacial centripetal and orthogonal strategies, suggesting some raw material independence (Antoine et al., 2019).

In summary, early Middle Pleistocene mode 2 European assemblages demonstrate distinct features in their core reduction sequences, such as a strong reliance on locally available raw materials, selective management of raw materials, a combination of complex and more expedient reduction strategies, the ability to overcome raw material constraints, longer reduction sequences compared to mode 1, evidence of independent production of both large and small flakes, an increasing occurrence of centripetal strategies, and a higher frequency and intensity of platform preparation (Gallotti & Peretto, 2015).

The cores found in the three BB localities share several aspects with these observations (Table 4). Furthermore, BB assemblages mainly focus on the production of small-sized flakes, with giant cores being notably absent. Despite this absence, the management of large volumes is confirmed by the existence of five large schist flakes (both retouched and unretouched).

B) Large-Shaped Tool Sequences

In the US4 level at Bois-de-Riquet, shaping sequences have been documented both from cobbles and from large flakes and are oriented towards obtaining cutting-edges limited to a specific sector of the blank, located at the opposite end of a prehensile surface, which generally occupies half the perimeter of the blanks. In the flakes, the configuration presents a greater perimeter development, generating a semi-peripheral edge. These heavy-duty tools can be either unifacial or bifacial and generally show little modification and a low degree of morphological standardization, ranging from cordiform to tools with transverse edges, although they do not correspond typologically to cleavers (Bourguignon et al., 2016a).

At Notarchirico, there are no clear differences between the different levels in terms of shaping processes or the final types. However, level F (< 670 ka) shows a greater diversity in the shaping and morphology of the handaxes, although their dimensions are very homogeneous. In contrast, more recent levels, such as B, show a higher frequency of less elaborated bifacial tools and a greater size diversity. In addition, in some levels, the presence of handaxes is accompanied by other shaped tools, such as choppers or pointed chopping tools (Moncel et al., 2019, 2020b).

At La Noira Stratum a, a variety of shaping processes have been identified (García-Medrano et al., 2022; Moncel et al., 2016, 2020a, 2021). These processes encompass (1) heavy-duty tools that feature partial modifications aimed at creating cutting edges, (2) bifacial tools shaped through peripheral extractions to produce convergent cutting edges without comprehensive volume management, (3) handaxes made from thinner blanks displaying complete volume management, and generating cordiform and triangular shapes through the use of hard and soft hammer percussion, as well as (4) bifacial cleavers and cleaver-like tools characterized by transverse cutting edges.

It is therefore possible to identify in the European context the existence of large-shaped tools that demonstrate a capability for bifacial volume management on a wide variety of raw materials and blanks. These large-shaped tools present a wide range of final shapes ranging from oval, cordate or pointed, as in the Moulin Quignon site (Antoine et al., 2019). In general, in assemblages without handaxes, few large cutting tools have been recorded and they are characterized by a low degree of formal standardization (Moncel et al., 2021).

Moncel and Ashton (2018) highlight the main characteristics observed in the shaping processes of the early Middle Pleistocene assemblages. These characteristics include the major use of local raw materials; a low frequency of handaxes, which are always associated with partial bifacial tools; diversity in the configuration processes; and variations in the shape of the handaxes. Furthermore, there is an infrequent use of large flakes to produce heavy-duty tools or as cores for flake production.

In relation to these aspects, the large-shaped tools found at El Barranc de la Boella are shaped from locally available raw materials, predominantly schist, with chert slabs being less common. Notably, picks stand out from these assemblages, displaying some morpho-technical standardization such as triangular cross-sections and a consistent shaping pattern involving few invasive removals on the distal part of the tool. The predominant pattern of bifacial shaping is alternate, although we have also observed cases of alternating bifacial flaking. The outcomes reveal robust, thick sections, moderately sinuous edges, and limited bifacial and bilateral symmetry (Ollé et al., 2023).

This morpho-technical standardization primarily revolves around the careful blank selection with more suitable natural shapes to produce picks, rather than focusing on creating long and complex shaping series as shown by the reduction intensity values. In some cases, shaping was restricted to two large invasive distal removals and minor adjustments on the lateral edges.

It is essential to remark that the El Barranc de la Boella lithic collection lacks classical handaxes, which are typically characterized as symmetrical tools with two lateral convex edges converging toward a pronounced tip, featuring a lenticular cross-section, and shaped across their entire perimeter through invasive bifacial removals. This absence distinguishes El Barranc de la Boella from later mode 2 assemblages. Finally, the use of flakes to create heavy tools has been documented in some cases, especially in the production of cleavers ($n = 2$), knives ($n = 2$) or even a pick. Cleavers also show some particularities, since they do not meet Tixier's classic definition (Tixier, 1957), which implies an untrimmed bit (Ollé et al., 2023).

El Barranc de la Boella: Local Evolution, Diffusion, or Population Arrival?

Although some authors have vaguely discussed the mode 2 character of El Barranc de la Boella (Méndez-Quintas et al., 2018; Santonja et al., 2016) based on "the presence of fragmented flakes and fragments in these localities" as well as the low number of LCTs recovered (Santonja et al., 2016), the data presented and discussed here, together with the increased number of large-shaped tools recovered (Ollé et al., 2023) with respect to previous studies (Mosquera et al., 2015, 2016), allow us to confirm the adscription of these localities as mode 2 (see Table 4). BB represents the first known occurrence so far of this behaviour in western Europe.

Regarding the debate on whether BB represents a local evolution, a population migration with new technological behaviours, or an example of technological diffusion, we see that the possible answer is highly dependent on the type of approach or elements of the lithic assemblage that we consider.

If we understand gradual changes as the result of a local evolutionary process, we could interpret that the gradual evolution in knapping strategies from the mode 1, BB sites, and early Middle Pleistocene assemblages with progressive changes favouring more comprehensive and structured volume management that overcomes raw material constraints, as seen in the increased use of centripetal strategies (Gallotti & Peretto, 2015), would reflect a possible local evolution from mode 1 technocomplexes. This is especially the case considering that the BB lithic assemblage presents some similarities not only with European mode 1 assemblages but also with early Middle Pleistocene assemblages (780–600 ka).

Nevertheless, these gradual changes do not appear to follow a linear and homogeneous pattern, as seen in longer archaeological sequences such as Notarchirico, where no major changes in core knapping strategies have been detected over time (Carpentieri et al., 2023; Moncel et al., 2019, 2020b). Furthermore, these changes in technological behaviour may or may not be accompanied by the presence of handaxes, as observed in Isernia la Pineta (Gallotti & Peretto, 2015), where no handaxes have been found, possibly due to the lack of adequately sized raw materials (Moncel & Ashton, 2018).

However, if we focus only in the large-shaped tools, we will have a completely different perspective regarding BB's position compared to other contemporary assemblages. This difference stems from the categorical classification, where mode 1 is defined as a technology based on core and flake technologies (Clark, 1969), and mode 2 is characterized by the presence of large-shaped tools, which does not allow for gradations.

In that way, large-shaped tools are typological constructions based on the presence of technical and morphological elements that in many cases are defined by presence or absence and not by degree. For example, in the case of handaxes, their definition is mainly based on the coexistence of two elements: symmetry and bifacial character (Villa, 2001). While new methods may quantify symmetry to some extent, the bifacial character can ultimately be summarized as categorical, and it is essentially binary — either bifacial or non-bifacial and does not accept intermediate degrees.

Consequently, using categorical variables to define an assemblage or some of its elements makes it difficult to identify transitional technologies or gradual technological changes. Although theoretically possible, such transitions would be challenging to distinguish in practice. In this scenario, the only traceable evidence for a possible origin of these large-shaped tools might come from the cores or some retouched elements (like chopping tools, becs, among others). Therefore, identifying a possible intermediate step to these large instruments is complex, if not impossible. This difficulty might explain the absence of transitional assemblages between both technocomplexes in the European record (Moncel et al., 2020a; Mosquera et al., 2016).

Regarding the position of BB assemblages with other European early Middle Pleistocene archaeological sites based on large-shaped tools types, we have seen that in the early Middle Pleistocene assemblages, large-shaped tools are predominantly characterized by bifacial management, where, despite a high degree of typological variability, picks and/or trihedrons are rare or absent. At BB, the large-shaped tools are primarily defined by the configuration of trihedron, either unifacial or bifacial, but morphologically trihedral. In contrast, bifacial management is mainly seen in the chopping-tools and the cleaver-like tool.

Some authors consider BB to be an earlier local evolution (see Carpentieri et al., 2023). However, we have seen the problems derived from the classifications themselves, in which it would be necessary to find transitional morphologies in the archaeological record, something that, considering the abrupt discontinuity shown by the European record in these chronologies (Key & Ashton, 2023), seems unlikely.

If we consider the entire technological record — beyond the large-shaped tools types — the behaviours identified in BB, regarding specific reduction sequences for different raw materials, blank selection for large-shaped tool production, large flake production, transport (spatiotemporal fragmentation of reduction sequences), and the existence of a mental procedural template inferred from the core knapping strategies, seem to represent a new set of technological behaviours not seen in the European mode 1 assemblages. These "background" technological characteristics are more similar to those found in other early Middle Pleistocene sites.

The existence of a common behavioural "substrate" that manifests itself differently according to local particularities such as the raw material availability, site function (Moncel & Ashton, 2018), or other factors such as the occupation type or intensity could explain a large part of the technological features of these assemblages. However, in other technological aspects, neither the available raw materials nor the intensity and type of occupations seem to be absolute responsible for some the technological characteristics such as large-shaped tool types in the case of BB. The existence of large-sized cores, together with the configuration of picks or cleavers, rules out raw material as an explanatory factor for the absence of handaxes. On the other hand, although the functionality of the different localities seems to condition the frequency of large-shaped tools, the presence of picks and cleavers seems to indicate that their existence is not exclusively linked to the type of occupation represented.

If the causes of these differences are not only due to physical aspects such as raw material availability or occupational factors, perhaps BB is representing a first arrival of an early mode 2 technology to the European continent — the first wave of a surge of hominin dispersal that happens during late Early Pleistocene and early Middle Pleistocene.

The non-linearity in the evolution of core knapping strategies together with the diversity of large shape tool production in this period (900–600 ka) also seems to point to the existence of multiple waves of hominin dispersals in which the BB sites represent the oldest know arrival of this technological set of behaviours.

If we accept a hominin dispersal hypothesis, the next question is: Where did these populations come from? Various potential dispersal routes have been proposed, such as the Gibraltar Strait (O'Regan, 2008) or the Aegean zone (Sakellariou & Galanidou, 2017; Tourloukis & Harvati, 2018). However, we consider the coastal route along the northern Mediterranean basin to be the most plausible hypothesis since shared technological elements between 'Ubeidiya and BB, including the differential use of raw materials tailored to specific goals, the emergence of large-shaped tools linked to a spatiotemporal fragmentation of reduction sequences, and the presence of picks, among other technological aspects (Herzlinger et al., 2021; Ollé et al., 2023). In this context, BB and 'Ubeidiya might represent different moments of the same hominin dispersal (Ollé et al., 2023). Subsequent "demographic waves", characterized by a more "classic" mode 2, could have occurred around 0.8 million years ago and might be associated with the large flake technology from Gesher Benot Ya'aqov (GBY) (Goren-Inbar et al., 2000). Detailed comparisons are necessary to explore the similarities between El Barranc de la Boella and 'Ubeidiya, and between GBY and early Middle Pleistocene mode 2 sites, to define their potential relationships more precisely.

Conclusion

We have conducted a comprehensive analysis of the lithic assemblages from three localities at El Barranc de la Boella, which represent the earliest appearance of the mode 2 technocomplex in Europe. Our study focused on five key technological aspects: (1) raw material management, (2) core reduction strategies, (3) reduction intensity and volumetric depletion, (4) large flake production (> 10 cm), and (5) integrity of reduction sequence, comparing these findings with earlier European mode 1 assemblages and subsequent early Middle Pleistocene mode 2 contexts to highlight the technological evolution in the late Early Pleistocene and early Middle Pleistocene.

The technological behaviour observed at BB demonstrates significant technological advancements and anticipatory behaviour. The existence of a procedural template inferred from core reduction strategies, coupled with the production of large-shaped tools characterized by a principle of gestural economy, as well as the presence of different reduction sequences tailored to specific purposes suggests a sophisticated level of foresight and planning.

Although the difficulty to find transitional assemblages, our findings suggest a greater likelihood of population dispersals rather than a local evolution from mode 1 to mode 2 technologies at BB.

Furthermore, although BB shares a technological "background" with early Middle Pleistocene sites, there are some technological differences, particularly in the types of large-shaped tools, that cannot be explained solely by the specific contexts of each site. This, along with the evidence of a non-linear evolution in core knapping strategies during the late Early Pleistocene and early Middle Pleistocene, points to the existence of migratory flows involving different population waves. In this scenario, BB may represent an early dispersal of the Acheulean from Africa around 1.4 million years ago, which may be related with 'Ubeidiya.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s41982-024-00189-9.

Acknowledgements We extend our gratitude to editor, Dr. Shannon P. McPherron and the reviewers for their valuable comments. We also thank all the participants in the El Barranc de la Boella fieldwork, and especially Oriol Cortés and the Boella staff for their assistance at the site. Special thanks to Görkem C. Yeşilova for providing the image used in Fig. 1.

Author Contribution D.L.: conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing-original draft, writing—review and editing, visualization, supervision, J.I.M.: validation, investigation, resources, data curation, writing-original draft, writing—review and editing, supervision M.M.: validation, investigation, resources, data curation, writing-original draft, writing—review and editing, supervision. A.O.: validation, investigation, resources, data curation, writing-original draft, writing—review and editing, visualization, supervision. P.S.: resources, data curation, writing-original draft, writing—review and editing, supervision, project administration, funding acquisition. J.V.: resources, data curation, writing-original draft, writing—review and editing, supervision, project administration, funding acquisition.

Funding El Barranc de la Boella fieldwork was supported by Ajuntament de la Canonja and the Departament de Cultura (Servei d'Arqueologia i Paleontologia) (CLT009/22/000024) of the Generalitat de Catalunya. Research was developed within the frame of the projects PID 2021-122355NB-C32 funded by MCIN/AEI/https://doi.org/10.13039/501100011033 and by "ERDF A way of making Europe", SGR 2021–01239, SGR 2021–01237, and SGR 2021–01238 (Catalan AGAUR), and 2023PFR-URV-01239 (URV). The Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA) has received financial support from the Spanish Ministry of Science and Innovation through the "María de Maeztu" program for Units of Excellence (CEX2019-000945-M). D.L. is funded by Post-Doc Xunta de Galicia Grant (ED481B-2022–048). The research of J.I.M. was supported by the Spanish Ministry of Science and Innovation through the "María de Maeztu" excellence accreditation (CEX2019-000945-M).

Data Availability All the materials studied here are temporally deposited at the Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA, Tarragona, Spain).

Declarations

Competing Interests The authors declare no competing interests.

References

Akhilesh, K., & Pappu, S. (2015). Bits and pieces: Lithic waste products as indicators of Acheulean behaviour at Attirampakkam India. *Journal of Archaeological Science: Reports, 4*, 226–241. https://doi.org/10.1016/j.jasrep.2015.08.045

Andrefsky, W. J. (1998). *Lithics: Macroscopic approaches to analysis. Cambridge Manuals in Archaeology*. New York: Cambridge University Press.

Antoine, P., Moncel, M. H., Voinchet, P., Locht, J.-L., Amselem, D., Hérisson, D., Hurel, A., & Bahain, J.-J. (2019). The earliest evidence of Acheulian occupation in Northwest Europe and the rediscovery of the Moulin Quignon site, Somme valley. *France. Sci. Rep., 9*, 13091. https://doi.org/10.1038/s41598-019-49400-w

Antón, S. C., Potts, R., & Aiello, L. C. (2014). Evolution of early Homo: An integrated biological perspective. *Science, 345*, 6192. https://doi.org/10.1126/science.1236828

Arzarello, M., Peretto, C., & Moncel, M. H. (2015). The Pirro Nord site (Apricena, Fg, Southern Italy) in the context of the first European peopling: Convergences and divergences. *Quaternary International, 389*, 255–263. https://doi.org/10.1016/J.QUAINT.2014.08.051

Arzarello, M., De Weyer, L., & Peretto, C. (2016). The first European peopling and the Italian case: Peculiarities and "opportunism." *Quaternary International, 393*, 41–50.

Ashton, N., 1992. The high lodge flint industries., in: Ashton, N., Cook, J., Lewis, S.J., Rose, J. (Eds.), High lodge. Excavations by G. de Sieveking, 1962–8, and J. Cook, 1988. British Museum Press, pp. 124–168.

Ashton, N. M., & McNabb, J. (1994). Bifaces in perspective. In N. Ashton & A. David (Eds.), *Stories in stone* (pp. 182–191). Lithic Studies Society.

Baena, J., Lordkipanidze, D., Cuartero, F., Ferring, R., Zhvania, D., Martín, D., Shelia, T., Bidzinashuili, G., Roca, M., & Rubio, D. (2010). Technical and technological complexity in the beginning: The study of Dmanisi lithic assemblage. *Quaternary International, 223–224*, 45–53. https://doi.org/10.1016/j.quaint.2010.01.019

Barsky, D., Vergès, J. M., Sala, R., Menéndez, L., & Toro-Moyano, I. (2015). Limestone percussion tools from the late Early Pleistocene sites of Barranco León and Fuente Nueva 3 (Orce, Spain). *Philos Trans R Soc London B Biol Sci, 370*, 20140352. https://doi.org/10.1098/rstb.2014.0352

Barsky, D., Titton, S., Sala-Ramos, R., Bargalló, A., Grégoire, S., Saos, T., Serrano-Ramos, A., Oms, O., Solano García, J.-A., Toro-Moyano, I., & Jiménez-Arenas, J. M. (2022). The significance of subtlety: Contrasting lithic raw materials procurement and use patterns at the Oldowan Sites of Barranco León and Fuente Nueva 3 (Orce, Andalusia, Spain). *Front. Earth Sci, 10*, 893776. https://doi.org/10.3389/feart.2022.893776

Bar-Yosef, O., & Goren-Inbar, N. (1993). The lithic assemblages of 'Ubeidiya: A Lower Palaeolithic Site in the Jordan Valley. *Qedem: Monographs of the Institute of Archaeology, 34*, 280.

Beyene, Y., Katoh, S., WoldeGabriel, G., Hart, W. K., Uto, K., Sudo, M., Kondo, M., Hyodo, M., Renne, P. R., Suwa, G., & Asfaw, B. (2013). The characteristics and chronology of the earliest Acheulean at Konso. *Ethiopia. Proc. Natl. Acad. Sci., 110*, 1584–1591. https://doi.org/10.1073/pnas.1221285110

Bourguignon, L., Barsky, D., Ivorra, J., de Weyer, L., Cuartero, F., Capdevila, R., Cavallina, C., Oms, O., Bruxelles, L., Crochet, J. Y., & Rios-Garaizar, J. (2016a). The stone tools from stratigraphical unit 4 of the Bois-de-Riquet site (Lézignan-la-Cèbe, Hérault, France): A new milestone in the diversity of the European Acheulian. *Quaternary International, 411*, 160–181. https://doi.org/10.1016/J.QUAINT.2016.01.065

Bourguignon, L., Crochet, J. Y., Capdevila, R., Ivorra, J., Antoine, P. O., Agustí, J., Barsky, D., Blain, H. A., Boulbes, N., Bruxelles, L., Claude, J., Cochard, D., Filoux, A., Firmat, C., Lozano-Fernández, I., Magniez, P., Pelletier, M., Rios-Garaizar, J., Testu, A., … De Weyer, L. (2016b). Bois-de-Riquet (Lézignan-la-Cèbe, Hérault): A late Early Pleistocene archeological occurrence in southern France. *Quaternary International, 393*, 24–40. https://doi.org/10.1016/J.QUAINT.2015.06.037

Bretzke, K., & Conard, N. J. (2012). Evaluating morphological variability in lithic assemblages using 3D models of stone artifacts.

Journal of Archaeological Science, 39, 3741–3749. https://doi.org/10.1016/j.jas.2012.06.039

Cachel, S., & Harris, J. W. K. (1998). The lifeways of Homo erectus inferred from archaeology and evolutionary ecology: A perspective from East Africa. In R. Korisettar & M. D. Petraglia (Eds.), *Lower Palaeolithic settlement of the Old World* (pp. 108–132). Routledge.

Carbonell, E., Guilbaud, M., & Mora, R. (1983). Utilización de la Lógica Analítica para el estudio de los tecnocomplejos a cantos tallados. *Cah. Noir, 1*, 3–64.

Carbonell, E., Mosquera, M., Ollé, A., Rodríguez-Álvarez, X. P., Sala, R., Vaquero, M., & Vergès, J. M. (1992). New elements of the logical analytical system. First International Meeting on Technical Systems to Configure Lithic Objects of scarce elaboration. *Cah Noir, 6*, 3–61.

Carbonell, E., García-Antón, M. D., Mallol, C., Mosquera, M., Ollé, A., Rodríguez-Álvarez, X. P., Sahnouni, M., Sala, R., & Vergès, J. M. (1999). The TD6 level lithic industry from Gran Dolina, Atapuerca (Burgos, Spain): Production and use. *Journal of Human Evolution, 37*, 653–693. https://doi.org/10.1006/jhev.1999.0336

Carbonell, E., Rodríguez-Álvarez, X. P., Parés, J. M., Huguet, R., & Rosell, J. (2024). The earliest human occupation of Atapuerca in the European context. *L'anthropologie, 128*, 103233. https://doi.org/10.1016/j.anthro.2024.103233

Carpentieri, M., & Arzarello, M. (2021). For our world without sound. The opportunistic debitage in the Italian context: A methodological evaluation of the lithic assemblages of Pirro Nord, Cà Belvedere di Montepoggiolo, Ciota Ciara cave and Riparo Tagliente. Reserved Sq. https://doi.org/10.21203/rs.3.rs-176361/v1.

Carpentieri, M., Moncel, M.-H., Eramo, G., & Arzarello, M. (2023). With impressions chosen from another time: Core technologies and debitage production at the lower Palaeolithic site of Notarchirico (670–695 ka; layers F to I2). *J. Paleolit. Archaeol., 6*, 27. https://doi.org/10.1007/s41982-023-00154-y

Cauche, D. (2009). Les stratégies de débitage dans les industries lithiques archaïques des premiers habitants de l'Europe. *L'anthropologie, 113*, 178–190. https://doi.org/10.1016/j.anthro.2009.01.012

Chase, P.G. (2008). Form, function, and mental templates in Paleolithic lithic analysis, in: Paper presented at the Symposium 'From the Pecos to the Paleolithic: Papers in Honor of Arthur J. Jelinek'. Society for American Anthropology Meetings, Vancouver, BC.

Chavaillon, J., & Berthelet, A. (2004). The archaeological sites of Melka Kunture. In J. Chavaillon & M. Piperno (Eds.), *Studies on the Early Paleolithic site of Melka Kunture, Ethiopia* (pp. 25–82). Florencia: Instituto Italiano di Preistoria e Protostoria.

Clark, G. (1969). *World prehistory: A new synthesis*. Cambridge University Press.

Clarkson, C. (2013). Measuring core reduction using 3D flake scar density: A test case of changing core reduction at Klasies River Mouth, South Africa. *Journal of Archaeological Science, 40*, 4348–4357. https://doi.org/10.1016/j.jas.2013.06.007

Clarkson, C., Vinicius, L., & Mirazón-Lahr, M. (2006). Quantifying flake scar patterning on cores using 3D recording techniques. *Journal of Archaeological Science, 33*, 132–142. https://doi.org/10.1016/j.jas.2005.07.007

Cole, J. (2015). Examining the presence of symmetry within Acheulean handaxes: A case study in the British Palaeolithic. *Cambridge Archaeological Journal, 25*, 713–732. https://doi.org/10.1017/S0959774315000141

Corbey, R., Jagich, A., Vaesen, K., & Collard, M. (2016). The acheulean handaxe: More like a bird's song than a beatles' tune? *Evolutionary Anthropology: Issues, News, Reviews, 25*, 6–19. https://doi.org/10.1002/evan.21467

Cueva-Temprana, A., Lombao, D., Morales, J. I., Geribàs, N., & Mosquera, M. (2019). Gestures during knapping: A two-perspective approach to Pleistocene technologies. *Lithic Technology, 44*, 74–89. https://doi.org/10.1080/01977261.2019.1587255

Cueva-Temprana, A., Lombao, D., Soto, M., Itambu, M., Bushozi, P., Boivin, N., Petraglia, M., & Mercader, J. (2022). Oldowan technology amid shifting environments ~2.03–1.83 million years ago. Frontiers of Ecological Evolution. 10. https://doi.org/10.3389/fevo.2022.78810

de la Torre, I. (2009). Technological strategies in the Lower Pleistocene at Peninj (West of Lake Natron, Tanzania). In K. Schick & N. Toth (Eds.), *The cutting edge: New approaches to the archaeology of human origins* (pp. 93–113). Stone Age I.

de la Torre, I. (2011). The Early Stone Age lithic assemblages of Gadeb (Ethiopia) and the developed Oldowan/early Acheulean in East Africa. *Journal of Human Evolution, 60*, 768–812.

de la Torre, I. (2016). The origins of the acheulean: Past and present perspectives on a major transition in human evolution. *Philosophical Transactions of the Royal Society B: Biological Sciences, 371*(1698), 20150245

de la Torre, I., & Mora, R. (2005). *Technological strategies in the Lower Pleistocene at Olduvai beds I and II*. Universite de Liege, Liege.

de la Torre, I., & Mora, R. (2014). The transition to the Acheulean in East Africa: An assessment of paradigms and evidence from Olduvai Gorge (Tanzania). *Journal of Archaeological Method and Theory, 21*, 781–823. https://doi.org/10.1007/s10816-013-9176-5

de la Torre, I., & Mora, R. (2018). Technological behaviour in the early Acheulean of EF-HR (Olduvai Gorge, Tanzania). *Journal of Human Evolution, 120*, 329–377. https://doi.org/10.1016/j.jhevol.2018.01.003

de la Torre, I., Mora, R., & Martínez-Moreno, J. (2008). The early Acheulean in Peninj (Lake Natron, Tanzania). *Journal of Anthropological Archaeology, 27*, 244–264. https://doi.org/10.1016/j.jaa.2007.12.001

de la Torre, I., & Mora, R. (2020). How many handaxes make an Acheulean? In: J. Cole, J. McNabb, M. Grove, & R. Hosfield (Eds.), *Landscapes of Human Evolution* (pp. 64–91). Archaeopress Publishing Ltd. https://doi.org/10.2307/j.ctvx5w983.9

de Lombera-Hermida, A., Bargalló, A., Terradillos-Bernal, M., Huguet, R., Vallverdú, J., García-Antón, M. D., Mosquera, M., Ollé, A., Sala, R., Carbonell, E., & Rodríguez-Álvarez, X. P. (2015). The lithic industry of Sima del Elefante (Atapuerca, Burgos, Spain) in the context of Early and Middle Pleistocene technology in Europe. *Journal of Human Evolution, 82*, 95–106. https://doi.org/10.1016/j.jhevol.2015.03.002

de Lombera-Hermida, A., Rodríguez-Álvarez, X. P., Peña, L., Sala-Ramos, R., Despriée, J., Moncel, M. H., Gourcimault, G., Voinchet, P., & Falguères, C. (2016). The lithic assemblage from Pont-de-Lavaud (Indre, France) and the role of the bipolar-on-anvil technique in the Lower and Early Middle Pleistocene technology. *Journal of Anthropological Archaeology, 41*, 159–184. https://doi.org/10.1016/j.jaa.2015.12.002

Despriée, J., Voinchet, P., Tissoux, H., Bahain, J.-J., Falguères, C., Courcimault, G., Dépont, J., Moncel, M.-H., Robin, S., Arzarello, M., Sala, R., Marquer, L., Messager, E., Puaud, S., & Abdessadok, S. (2011). Lower and Middle Pleistocene human settlements recorded in fluvial deposits of the middle Loire River Basin, Centre Region. *France. Quat. Sci. Rev., 30*, 1474–1485. https://doi.org/10.1016/j.quascirev.2011.02.011

Despriée, J., Voinchet, P., Courcimault, G., Hardy, B., Bahain, J., Puaud, S., Gallet, X., & Falgu, C. (2015). The Acheulean workshop of la Noira (France, 700 ka) in the European technological context. *Quaternary International, 393*, 112–136. https://doi.org/10.1016/j.quaint.2015.04.051

Despriée, J., Voinchet, P., Courcimault, G., Bahain, J.-J., Puaud, S., Moreno, D., Chantreau, Y., Tissoux, H., Gallet, X., Chapon Sao, C., Abdessadok, S., & Falguères, C. (2017). Le site pléistocène moyen de la Noira à Brinay (Cher, région Centre, France): Contexte morphosédimentaire, géochronologie et données archéologiques. *Quaternaire, 28*, 31–48. https://doi.org/10.4000/quaternaire.7900

Despriée, J., Moncel, M. H., Arzarello, M., Courcimault, G., Voinchet, P., Bahain, J. J., & Falguères, C. (2018). The 1-million-year-old quartz assemblage from Pont-de-Lavaud (Centre, France) in the European context. *Journal of Quaternary Science, 33*, 639–661. https://doi.org/10.1002/JQS.3042

Dibble, H. L. (1995). Biache Saint-Vaast, Level IIA: A comparison of analytical approaches. In H. L. Dibble & O. Bar-Yosef (Eds.), *The definition and interpretation of Levallois technology. Monographs in World Archaeology 23* (pp. 93–116). Madison: Prehistory Press.

Diez-Martín, F., Sánchez Yustos, P., Uribelarrea, D., Baquedano, E., Mark, D. F., Mabulla, A., Fraile, C., Duque, J., Díaz, I., Pérez-González, A., Yravedra, J., Egeland, C. P., Organista, E., & Domínguez-Rodrigo, M. (2016). The origin of the Acheulean: The 1.7 million-year-old site of FLK West, Olduvai Gorge (Tanzania). *Sci. Rep., 5*, 17839. https://doi.org/10.1038/srep17839

Douglass, M. J., Lin, S. C., Braun, D. R., & Plummer, T. W. (2018). Core use-life distributions in lithic assemblages as a means for reconstructing behavioral patterns. *Journal of Archaeological Method and Theory, 25*, 254–288. https://doi.org/10.1007/s10816-017-9334-22

Duval, M., Grün, R., Parés, J. M., Campaña, I., Martín-Francés, L., Rosell, J., Shao, Q., Arsuaga, J. L., Carbonell, E., & Bermúdez de Castro, J. M. (2018). The first direct ESR dating of a hominin tooth from Atapuerca Gran Dolina TD-6 (Spain) supports the antiquity of Homo antecessor. *Quaternary Geochronology, 47*, 120–137. https://doi.org/10.1016/j.quageo.2018.05.001

Fedato, A., Silva-Gago, M., Terradillos-Bernal, M., Alonso-Alcalde, R., & Bruner, E. (2020). Hand grasping and finger flexion during Lower Paleolithic stone tool ergonomic exploration. *Archaeological and Anthropological Sciences, 12*, 254. https://doi.org/10.1007/s12520-020-01189-w

Fidalgo, D., Rosas, A., Estalrrich, A., García-Tabernero, A., Pastor, F. J., Pineda, A., Huguet, R., Cáceres, I., Ollé, A., Vallverdú, J., & Saladie, P. (2023). First presence of Macaca sylvanus at the late Early Pleistocene of Barranc de la Boella (La Mina locality, Francolí Basin, NE Iberia). *Journal of Human Evolution, 179*, 103368. https://doi.org/10.1016/j.jhevol.2023.103368

Finkel, M., & Barkai, R. (2018). The Acheulean handaxe technological persistence: A case of preferred cultural conservatism? *Proceedings of the Prehistoric Society, 84*, 1–19. https://doi.org/10.1017/PPR.2018.2

Forestier, H. (1993). Le Clactonien: Mise en application d'une nouvelle méthode de débitage s'inscrivant dans la variabilité des systèmes de production lithique du Paléolithique ancien. Paléo. *Rev. D'archéologie Préhistorique, 5*, 53–82. https://doi.org/10.3406/PAL.1993.1104

Gallotti, R. (2013). An older origin for the Acheulean at Melka Kunture (Upper Awash, Ethiopia): Techno-economic behaviours at Garba IVD. *Journal of Human Evolution, 65*, 594–620. https://doi.org/10.1016/J.JHEVOL.2013.07.001

Gallotti, R., & Mussi, M. (2018). The emergence of the Acheulean in East Africa and beyond, The emergence of the Acheulean in East Africa: Historical perspectives and current issues, vertebrate paleobiology and paleoanthropology. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-75985-2

Gallotti, R., & Peretto, C. (2015). The Lower/early Middle Pleistocene small débitage productions in Western Europe: New data from Isernia La Pineta t.3c (Upper Volturno Basin, Italy). *Quaternary International, 357*, 264–281. https://doi.org/10.1016/J.QUAINT.2014.06.055

García-Antón, M. D. (2016). *La captación, selección y gestión de recursos líticos en la prehistoria: Una visión diacrónica del uso del territorio y sus recursos en el entorno de la Sierra de Atapuerca (Burgos) durante el Pleistoceno Inferior y Medio*. Universitat Rovira i Virgili.

García-Medrano, P., Ollé, A., Ashton, N., & Roberts, M. B. (2019). The mental template in handaxe manufacture: New insights into Acheulean lithic technological behavior at Boxgrove, Sussex, UK. *Journal of Archaeological Method and Theory, 26*, 396–422. https://doi.org/10.1007/S10816-018-9376-0

García-Medrano, P., Ashton, N., Moncel, M.-H., & Ollé, A. (2020a). The WEAP method: A new age in the analysis of the Acheulean handaxes. *J. Paleolit. Archaeol., 3*, 756–793. https://doi.org/10.1007/S41982-020-00054-5

García-Medrano, P., Maldonado-Garrido, E., Ashton, N., & Ollé, A. (2020b). Objectifying processes: The use of geometric morphometrics and multivariate analyses on Acheulean tools. *Journal of Lithic Studies*. 7. https://doi.org/10.2218/JLS.4327

García-Medrano, P., Despriée, J., & Moncel, M.-H. (2022). Innovations in Acheulean biface production at la Noira (France) during Middle Pleistocene in Western Europe. *Archaeological and Anthropological Sciences, 14*, 69. https://doi.org/10.1007/s12520-022-01506-5

Geribàs, N., Mosquera, M., & Vergès, J. M. (2010). What novice knappers have to learn to become expert stone toolmakers. *Journal of Archaeological Science, 37*, 2857–2870. https://doi.org/10.1016/j.jas.2010.06.026

Goren-Inbar, N. (2011). Culture and cognition in the Acheulian industry: A case study from Gesher Benot Yaqov. *Philosophical Transactions of the Royal Society of London. Series B, 366*, 1038–1049. https://doi.org/10.1098/rstb.2010.0365

Goren-Inbar, N., Feibel, C. S., Verosub, K. L., Melamed, Y., Kislev, M. E., Tchernov, E., & Saragusti, I. (2000). Pleistocene milestones on the out-of-Africa corridor at Gesher Benot Ya'aqov, Israel. *Science, 289*(5481), 944–947. https://doi.org/10.1126/science.289.5481.944

Gowlett, J. A. J. (1984). Mental abilities of early man: A look at some hard evidence. In R. A. Foley (Ed.), *Hominid evolution and community ecology: Prehistoric human adaptation in biological perspective* (pp. 167–192). Academic Press.

Gowlett, J. A. J. (1986). Culture and conceptualisation: The Oldowan-Acheulian gradient. In G. N. Bailey & P. Callow (Eds.), *Stone age prehistory* (pp. 243–260). Cambridge University Press.

Gowlett, J., Gamble, C., & Dunbar, R. (2012). Human evolution and the archaeology of the social brain. *Current Anthropology, 53*, 693–722. https://doi.org/10.1086/667994

Groucutt, H. S., Shipton, C., Alsharekh, A., Jennings, R., Scerri, E. M. L., & Petraglia, M. D. (2015). Late Pleistocene lakeshore settlement in northern Arabia: Middle Palaeolithic technology from Jebel Katefeh Jubbah. *Quaternary International, 382*, 215–236. https://doi.org/10.1016/j.quaint.2014.12.001

Guilbaud, M. (1995). Introduction sommaire au concept de champ opératoire. *Cahier noir, 7*, 121–133.

Hardy, B. L., Moncel, M. H., Despriée, J., Courcimault, G., & Voinchet, P. (2018). Middle Pleistocene hominin behavior at the 700ka Acheulean site of la Noira (France). *Quaternary Science Reviews, 199*, 60–82. https://doi.org/10.1016/j.quascirev.2018.09.013

Herzlinger, G., & Grosman, L. (2018). AGMT3-D: A software for 3-D landmarks-based geometric morphometric shape analysis of archaeological artifacts. *PloS one, 13*(11), e0207890. https://doi.org/10.1371/JOURNAL.PONE.0207890

Herzlinger, G., Goren-Inbar, N., & Grosman, L. (2017). A new method for 3D geometric morphometric shape analysis: The case study of handaxe knapping skill. *Journal of Archaeological Science: Reports, 14*, 163–173. https://doi.org/10.1016/J.JASREP.2017.05.013

Herzlinger, G., Brenet, M., Varanda, A., Deschamps, M., & Goren-Inbar, N. (2021). Revisiting the Acheulian large cutting tools of 'Ubeidiya Israel. *Journal of Paleolithic Archaeology, 4*, 31. https://doi.org/10.1007/s41982-021-00108-2

Hodgson, D. (2009). Evolution of the visual cortex and the emergence of symmetry in the Acheulean techno-complex. *Comptes Rendus Palevol, 8*(1), 93–97. https://doi.org/10.1016/j.crpv.2008.10.009

Hodgson, D. (2011). The first appearance of symmetry in the human lineage: Where perception meets art. *Symmetry, 3*(1), 37–53. https://doi.org/10.3390/sym3010037

Hodgson, D. (2015). The symmetry of Acheulean handaxes and cognitive evolution. *Journal of Archaeological Science: Reports, 2*, 204–208. https://doi.org/10.1016/j.jasrep.2015.02.002

Hoggard, C. S., McNabb, J., & Cole, J. N. (2019). The application of elliptic Fourier analysis in understanding biface shape and symmetry through the British Acheulean. *Journal of Paleolithic Archaeology, 2*, 115–133. https://doi.org/10.1007/s41982-019-00024-6

Inizan, M.L., Reduron-Ballinger, M., Roche, H., & Tixier, J. (1999). Technology and terminology of knapped stone. In: Préhistoire de La Pierre Taillée. Cercle de Recherches et d'Études Préhistoriques, Paris.

Iovită, R., Tuvi-Arad, I., Moncel, M. H., Despriée, J., Voinchet, P., & Bahain, J.-J. (2017). High handaxe symmetry at the beginning of the European Acheulian: The data from la Noira (France) in context. *PLoS ONE, 12*, e0177063. https://doi.org/10.1371/JOURNAL.PONE.0177063

Isaac, G. L. I. (1977). *Olorgesailie. Archeological studies of a Middle Pleistocene Lake Basin in Kenya*. University of Chicago Press.

Jones, P. R. (1979). Effects of raw materials on biface manufacture. *Science, 204*(4395), 835–836. https://doi.org/10.1126/SCIENCE.204.4395.835

Key, A., & Ashton, N. (2023). Hominins likely occupied northern Europe before one million years ago. *Evolutionary Anthropology: Issues, News, and Reviews, 32*, 10–25. https://doi.org/10.1002/evan.21966

Key, A. J. M., & Lycett, S. J. (2017). Influence of handaxe size and shape on cutting efficiency: A large-scale experiment and morphometric analysis. *Journal of Archaeological Method and Theory, 24*, 514–541. https://doi.org/10.1007/s10816-016-9276-0

Key, A. J. M., Proffitt, T., Stefani, E., & Lycett, S. J. (2016). Looking at handaxes from another angle: Assessing the ergonomic and functional importance of edge form in Acheulean bifaces. *Journal of Anthropological Archaeology, 44*, 43–55. https://doi.org/10.1016/j.jaa.2016.08.002

Kuman, K., & Gibbon, R. J. (2018). The Rietputs 15 site and Early Acheulean in South Africa. *Quaternary International, 480*, 4–15. https://doi.org/10.1016/j.quaint.2016.12.031

Laplace, G. (1972). La typologie analytique et structurale: Base rationnelle d´étude des industries lithiques et osseuses. *Colloquia Natx CNRS, 932*, 91–143.

Leader, G. M. (2014). *New excavations at Canteen Kopje, Northern Cape Province, South Africa: A techno-typological comparison of three earlier Acheulean assemblages with new interpretations on the Victoria West phenomenon*. Ph.D, University of the Witwatersrand. Available at https://www.hdl.handle.net10539/14846

Leader, G. M., Kuman, K., Gibbon, R. J., & Granger, D. E. (2018). Early Acheulean organised core knapping strategies ca. 1.3 Ma at Rietputs 15, Northern Cape Province, South Africa. *Quaternary International, 480*, 16–28. https://doi.org/10.1016/j.quaint.2016.08.046

Lepre, C. J., Roche, H., Kent, D. V., Harmand, S., Quinn, R. L., Brugal, J.-P., Texier, P.-J., Lenoble, A., & Feibel, C. S. (2011). An earlier origin for the Acheulian. *Nature, 477*, 82–85. https://doi.org/10.1038/nature10372

Li, H., Kuman, K., & Li, C. (2015). Quantifying the reduction intensity of handaxes with 3D technology: A pilot study on handaxes in the Danjiangkou Reservoir Region Central China. *Plos One, 10*, e0135613. https://doi.org/10.1371/journal.pone.0135613

Lin, S. C., Douglass, M. J., Holdaway, S. J., & Floyd, B. (2010). The application of 3D laser scanning technology to the assessment of ordinal and mechanical cortex quantification in lithic analysis. *Journal of Archaeological Science, 37*, 694–702. https://doi.org/10.1016/j.jas.2009.10.030

Lombao, D. (2021). *Reducción y gestión volumétrica: aproximación a la variabilidad y evolución de las dinámicas de explotación durante el Pleistoceno inferior y medio europeo, a través de los conjuntos de Gran Dolina y Galería (Sierra de Atapuerca, Burgos) y de El Barranc de la Boella (La Canonja, Tarragona)*. Ph.D, Dept. Història i història de l'Art, Universitat Rovira i Virgili. Available at: https://www.hdl.handle.net/10803/673185

Lombao, D., Cueva-Temprana, A., Rabuñal, J. R., Morales, J. I., & Mosquera, M. (2019). The effects of blank size and knapping strategy on the estimation of core's reduction intensity. *Archaeological and Anthropological Sciences, 11*, 5445–5461. https://doi.org/10.1007/s12520-019-00879-4

Lombao, D., Cueva-Temprana, A., Mosquera, M., & Morales, J. I. (2020). A new approach to measure reduction intensity on cores and tools on cobbles: The volumetric reconstruction method. *Archaeological and Anthropological Sciences, 12*(9), 222. https://doi.org/10.1007/s12520-020-01154-7

Lombao, D., Falcucci, A., Moos, E., & Peresani, M. (2023). Unravelling technological behaviors through core reduction intensity The case of the early Protoaurignacian assemblage from Fumane Cave. *Journal of Archaeological Science, 160*, 105889. https://doi.org/10.1016/j.jas.2023.105889

Lombao, D., Rabuñal, J. R., Cueva-Temprana, A., Mosquera, M., & Morales, J. I. (2023b). Establishing a new workflow in the study of core reduction intensity and distribution. *Journal of Lithic Studies, 10*, 25. https://doi.org/10.2218/jls.7257

Lombao, D., Rabuñal, J. R., Morales, J. I., Ollé, A., Carbonell, E., & Mosquera, M. (2023c). The technological behaviours of Homo antecessor: Core management and reduction intensity at Gran Dolina-TD6.2 (Atapuerca, Spain). *Journal of Archaeological Method and Theory, 30*, 964–1001. https://doi.org/10.1007/s10816-022-09579-1

Lombao, D., Morales, J. I., Mosquera, M., Ollé, A., Saladié, P., & Vallverdú, J. (2024). *Research compendium for "Beyond large shaped tools: Technological innovations and continuities at the late Early Pleistocene assemblage of Barranc de la Boella (Tarragona, Spain)."* Zenodo. https://doi.org/10.5281/zenodo.10635057

Lordkipanidze, D., Jashashvili, T., Vekua, A., de León, M. S. P., Zollikofer, C. P. E., Rightmire, G. P., Pontzer, H., Ferring, R., Oms, O., Tappen, M., Bukhsianidze, M., Agustí, J., Kahlke, R., Kiladze, G., Martínez-Navarro, B., Mouskhelishvili, A., Nioradze, M., & Rook, L. (2007). Postcranial evidence from early Homo from Dmanisi, Georgia. *Nature, 499*, 305–310. https://doi.org/10.1038/nature06134

Lozano-Fernández, I., Bañuls-Cardona, S., Blain, H. A., López-García, J. M., Vallverdú, J., Agustí, J., & Cuenca-Bescós, G. (2014). Biochronological data inferred from the Early Pleistocene small mammals of the Barranc de la Boella site (Tarragona, north-eastern Spain). *Journal of Quaternary Science, 29*(7), 722–728. https://doi.org/10.1002/jqs.2744

Machin, A. J., Hosfield, R. T., & Mithen, S. J. (2007). Why are some handaxes symmetrical? Testing the influence of handaxe morphology on butchery effectiveness. *Journal of Archaeological Science, 34*(6), 883–893. https://doi.org/10.1016/j.jas.2006.09.008

Madurell-Malapeira, J., Sorbelli, L., Ros-Montoya, S., Martínez-Navarro, B., Vallverdú, J., Pineda, A., Rosas, A., Huguet, R., Cáceres, I., García-Tabernero, A., López-Polín, L., Ollé, A., & Saladié, P. (2019). Acheulian tools and Villafranchian taxa: The latest Early Pleistocene large mammal assemblage from Barranc de la Boella (NE Iberian Peninsula). In: XXXV Jornadas de Paleontología. pp. 161–166.

Mann, H. B., & Whitney, D. R. (1947). On a test of whether one of two random variables is stochastically larger than the other. *The Annals of Mathematical Statistics, 18*, 50–60. https://doi.org/10.1214/aoms/1177730491

Massey, F. J. (1951). The Kolmogorov-Smirnov test for goodness of fit. *Journal of American Statistical Association, 46*, 68–78. https://doi.org/10.1080/01621459.1951.10500769

Mcnabb, J., & Cole, J. (2015). The mirror cracked: Symmetry and refinement in the Acheulean handaxe. *Journal of Archaeological Science: Reports, 3*, 100–111. https://doi.org/10.1016/j.jasrep.2015.06.004

McPherron, S. P. (1994). *A reduction model for variability in Acheulian biface morphology*. University of Pennsylvania.

McPherron, S. P. (1995). A reexamination of the british biface data. *Lithics, 16*, 47–63.

McPherron, S. P. (2000). Handaxes as a measure of the mental capabilities of early hominids. *Journal of Archaeological Science, 27*, 655–663. https://doi.org/10.1006/jasc.1999.0467

Méndez-Quintas, E., Santonja, M., Pérez-González, A., Duval, M., Demuro, M., & Arnold, L. J. (2018). First evidence of an extensive Acheulean large cutting tool accumulation in Europe from Porto Maior (Galicia, Spain). *Science and Reports, 8*, 3082. https://doi.org/10.1038/s41598-018-21320-1

Mgeladze, A., Lordkipanidze, D., Moncel, M. H., Despriee, J., Chagelishvili, R., Nioradze, M., & Nioradze, G. (2010). First human settlement of the Caucasus: Technical behavior and raw material acquisition at Dmanisi, Georgia (1.77Ma). *Quaternary International, 223–224*, 422–425. https://doi.org/10.1016/j.quaint.2009.07.015

Michel, V., Shen, C.-C., Woodhead, J., Hu, H.-M., Wu, C.-C., Moullé, P. -É., Khatib, S., Cauche, D., Moncel, M.-H., Valensi, P., Chou, Y.-M., Gallet, S., Echassoux, A., Orange, F., & de Lumley, H. (2017). New dating evidence of the early presence of hominins in Southern Europe. *Scientific Reports, 7*(1), 10074. https://doi.org/10.1038/s41598-017-10178-4

Moncel, M. H., & Ashton, N. (2018). From 800 to 500 ka in Western Europe. The oldest evidence of Acheuleans in their technological, chronological, and geographical framework. In: R. Gallotti & M. Mussi (Eds.), *The emergence of the Acheulean in East Africa and beyond: Contributions in Honor of Jean Chavaillon* (pp 215–235). Springer. https://doi.org/10.1007/978-3-319-75985-2_11

Moncel, M.H., Despriée, J., Voinchet, P., Tissoux, H., Moreno, D., Bahain, J.J., Courcimault, G., & Falguères, C. (2013). Early evidence of acheulean settlement in northwestern Europe - La noira site, a 700 000 year-old occupation in the center of France. *PLoS One* 8. https://doi.org/10.1371/JOURNAL.PONE.0075529

Moncel, M. H., Despriée, J., Voinchet, P., Courcimault, G., Hardy, B., Bahain, J. J., Puaud, S., Gallet, X., & Falguères, C. (2016). The Acheulean workshop of la Noira (France, 700 ka) in the European technological context. *Quaternary International, 393*, 112–136. https://doi.org/10.1016/J.QUAINT.2015.04.051

Moncel, M. H., Despriée, J., Courcimaut, G., Voinchet, P., & Bahain, J.-J. (2020a). La Noira Site (Centre, France) and the technological behaviours and skills of the earliest Acheulean in Western Europe between 700 and 600 ka. *Journal of Paleolithic Archaeology, 3*, 255–301. https://doi.org/10.1007/S41982-020-00049-2

Moncel, M.-H., García-Medrano, P., Despriée, J., Arnaud, J., Voinchet, P., & Bahain, J.-J. (2021). Tracking behavioral persistence and innovations during the Middle Pleistocene in Western Europe. Shift in occupations between 700 and 450 ka at la Noira site (Centre, France). *J Hum Evol, 156*, 103009. https://doi.org/10.1016/j.jhevol.2021.103009

Moncel, M.H., Santagata, C., Pereira, A., Nomade, S., Bahain, J.J., Voinchet, P., & Piperno, M. (2019). A biface production older than 600 ka ago at Notarchirico (Southern Italy) contribution to understanding early Acheulean cognition and skills in Europe. *PLoS One* 14. https://doi.org/10.1371/JOURNAL.PONE.0218591

Moncel, M.H., Santagata, C., Pereira, A., Nomade, S., Voinchet, P., Bahain, J.-J., Daujeard, C., Curci, A., Lemorini, C., Hardy, B., Eramo, G., Berto, C., Raynal, J.-P., Arzarello, M., Mecozzi, B., Iannucci, A., Sardella, R., Allegretta, I., Delluniversità, E., Terzano, R., Dugas, P., Jouanic, G., Queffelec, A., D'andrea, A., Valentini, R., Minucci, E., Carpentiero, L., & Piperno, M. (2020b). The origin of early Acheulean expansion in Europe 700 ka ago: New findings at Notarchirico (Italy). Scientific Reports. 10. https://doi.org/10.1038/s41598-020-68617-8

Mosquera, M., Saladié, P., Ollé, A., Cáceres, I., Huguet, R., Villalaín, J. J., Carrancho, A., Bourlès, D., Braucher, R., & Vallverdú, J. (2015). Barranc de la Boella (Catalonia, Spain): An Acheulean elephant butchering site from the European late Early Pleistocene. *Journal of Quaternary Science, 30*, 651–666. https://doi.org/10.1002/JQS.2800

Mosquera, M., Ollé, A., Saladié, P., Cáceres, I., Huguet, R., Rosas, A., Villalaín, J. J., Carrancho, A., Bourlès, D., Braucher, R., Pineda, A., & Vallverdú, J. (2016). The Early Acheulean technology of Barranc de la Boella (Catalonia, Spain). *Quaternary International, 393*, 95–111. https://doi.org/10.1016/j.quaint.2015.05.005

Mosquera, M., Ollé, A., Rodríguez-Álvarez, X. P., & Carbonell, E. (2018). Shedding light on the Early Pleistocene of TD6 (Gran Dolina, Atapuerca, Spain): The technological sequence and occupational inferences. *PLoS ONE, 13*, e0190889. https://doi.org/10.1371/journal.pone.0190889

Muller, A., & Clarkson, C. (2016). Identifying major transitions in the evolution of lithic cutting edge production rates. *PLoS one, 11*(12), e0167244. https://doi.org/10.1371/journal.pone.0167244

Muller, A., Clarkson, C., & Shipton, C. (2017). Measuring behavioural and cognitive complexity in lithic technology throughout human evolution. *Journal of Anthropological Archaeology, 48*, 166–180. https://doi.org/10.1016/j.jaa.2017.07.006

O'Regan, H. (2008). The Iberian Peninsula – Corridor or cul-de-sac? Mammalian faunal change and possible routes of dispersal in the last 2 million years. *Quaternary Science Reviews, 27*, 2136–2144. https://doi.org/10.1016/j.quascirev.2008.08.007

Ollé, A., Mosquera, M., Rodríguez, X. P., de Lombera-Hermida, A., García-Antón, M. D., García-Medrano, P., Peña, L., Menéndez, L., Navazo, M., Terradillos-Bernal, M., Bargalló, A., Márquez, B., Sala, R., & Carbonell, E. (2013). The Early and Middle Pleistocene technological record from Sierra de Atapuerca (Burgos, Spain). *Quaternary International, 295*, 138–167. https://doi.org/10.1016/j.quaint.2011.11.009

Ollé, A., Lombao, D., Asryan, L., García-Medrano, P., Arroyo, A., Fernández-Marchena, J. L., Yeşilova, G. C., Cáceres, I., Huguet, R., López-Polín, L., Pineda, A., García-Tabernero, A., Fidalgo, D., Rosas, A., Saladié, P., & Vallverdú, J. (2023). The earliest European Acheulean: New insights into the large shaped tools from the late Early Pleistocene site of Barranc de la Boella (Tarragona, Spain). *Frontiers in Earth Science, 11*, 1188663. https://doi.org/10.3389/feart.2023.1188663

Pappu, S., & Akhilesh, K. (2019). Tools, trails and time: Debating Acheulian group size at Attirampakkam. *India. J. Hum. Evol., 130*, 109–125. https://doi.org/10.1016/j.jhevol.2019.02.004

Pappu, S., Gunnell, Y., Akhilesh, K., Braucher, R., Taieb, M., Demory, F., & Thouveny, N. (2011). Early Pleistocene presence of Acheulian hominins in South India. *Science, 331*(6024), 1596–1599. https://doi.org/10.1126/science.1200183

Parfitt, S. A., Barendregt, R. W., Breda, M., Candy, I., Collins, M. J., Coope, G. R., Durbidge, P., Field, M. H., Lee, J. R., Lister, A. M., Mutch, R., Penkman, K. E. H., Preece, R. C., Rose, J., Stringer, C. B., Symmons, R., Whittaker, J. E., Wymer, J. J., & Stuart, A. J. (2005). The earliest record of human activity in northern Europe. *Nature, 438*, 1008–1012. https://doi.org/10.1038/nature04227

Parfitt, S. A., Ashton, N. M., Lewis, S. G., Abel, R. L., Coope, G. R., Field, M. H., Gale, R., Hoare, P. G., Larkin, N. R., Lewis, M. D., Karloukovski, V., Maher, B. A., Peglar, S. M., Preece, R. C., Whittaker, J. E., & Stringer, C. B. (2010). Early Pleistocene human occupation at the edge of the boreal zone in northwest Europe. *Nature, 466*, 229–233. https://doi.org/10.1038/nature09117

Pearson, K. (1896). VII. Mathematical contributions to the theory of evolution.—III. Regression, heredity, and panmixia. *Philosophical Transactions of the Royal Society of London Series A, containing papers of a mathematical or physical character, 187*, 253–318. https://doi.org/10.1098/rsta.1896.0007

Pearson, K. (1900). X. On the criterion that a given system of deviations from the probable in the case of a correlated system of variables is such that it can be reasonably supposed to have arisen from random sampling. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 50*(302), 157–175. https://doi.org/10.1080/14786440009463897

Peretto, C., Amore, F., Antoniazzi, A., Antoniazzi, A., Bahain, J., Cattani, L., Cavallini, E., Esposito, P., Falguères, C., Gagnepain, J., Hedley, I., Laurent, M., Lebreton, V., Longo, L., Milliken, S., Monegatti, P., Ollé, A., Pugliese, N., Renault-Miskovsky, J., … Yokoyama, Y. (1998). L'industrie lithique de Ca'Belvedere di Monte Poggiolo: Stratigraphie, matière première, typologie, remontages et traces d'utilisation. *L'anthropologie, 102*, 1–120.

Pineda, A. (2018). *El rol de los homininos en la formación de conjuntos arqueo-paleontológicos al aire libre: La Mina y el Forn (Barranc de la Boella, la Canonja, Tarragona) y Torralba (Torralba del Moral, Soria)*. Universitat Rovira i Virgili.

Pineda, A., Saladié, P., Vergès, J. M., Huguet, R., Cáceres, I., & Vallverdú, J. (2014). Trampling versus cut marks on chemically altered surfaces: An experimental approach and archaeological application at the Barranc de la Boella site (la Canonja, Tarragona, Spain). *Journal of Archaeological Science, 50*, 84–93. https://doi.org/10.1016/J.JAS.2014.06.018

Pineda, A., Saladié, P., Huguet, R., Cáceres, I., Rosas, A., García-Tabernero, A., Estalrrich, A., Mosquera, M., Ollé, A., & Vallverdú, J. (2015). Coexistence among large predators during the Lower Paleolithic at the site of La Mina (Barranc de la Boella, Tarragona, Spain). *Quaternary International, 388*, 177–187. https://doi.org/10.1016/J.QUAINT.2015.05.006

Pineda, A., Saladié, P., Expósito, I., Rodríguez-Hidalgo, A., Cáceres, I., Huguet, R., Rosas, A., López-Polín, L., Estalrrich, A., García-Tabernero, A., & Vallverdú, J. (2017a). Characterizing hyena coprolites from two latrines of the Iberian Peninsula during the Early Pleistocene: Gran Dolina (Sierra de Atapuerca, Burgos) and la Mina (Barranc de la Boella, Tarragona). *Palaeogeography, Palaeoclimatology, Palaeoecology, 480*, 1–17. https://doi.org/10.1016/J.PALAEO.2017.04.021

Pineda, A., Saladié, P., Huguet, R., Cáceres, I., Rosas, A., Estalrrich, A., García-Tabernero, A., & Vallverdú, J. (2017b). Changing competition dynamics among predators at the late Early Pleistocene site Barranc de la Boella (Tarragona, Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology, 477*, 10–26. https://doi.org/10.1016/J.PALAEO.2017.03.030

Pineda, A., Cáceres, I., Saladié, P., Huguet, R., Morales, J. I., Rosas, A., & Vallverdú, J. (2019). Tumbling effects on bone surface modifications (BSM): An experimental application on archaeological deposits from the Barranc de la Boella site (Tarragona, Spain). *Journal of Archaeological Science, 102*, 35–47.

Putt, S. S., Woods, A. D., & Franciscus, R. G. (2014). The role of verbal interaction during experimental bifacial stone tool manufacture. *Lithic Technology, 39*, 96–112. https://doi.org/10.1179/0197726114Z.00000000036

R Core Team. (2022). *R: A language and environment for statistical computing*. Austria.

Roche, H., Brugal, J.-P., Delagnes, A., Feibel, C., Harmand, S., Kibunjia, M., Prat, S., & Texier, P.-J. (2003). Les sites archéologiques plio-pléistocènes de la formation de Nachukui, Ouest-Turkana, Kenya : Bilan synthétique 1997–2001. *Comptes Rendus Palevol, 2*, 663–673. https://doi.org/10.1016/j.crpv.2003.06.001

Rodríguez-Álvarez, X. P. (2004). *Technical systems of lithic production in the Lower and Middle pleistocene of the Iberian Peninsula: Technological variability between north-eastern sites and Sierra de Atapuerca sites*. BAR International Series.

Rosas, A., Saladié, P., Huguet, R., Cáceres, I., Pineda, A., Ollé, A., Mosquera, M., García-Tabernero, A., Estalrrich, A., Pérez-Criado, L., Rodríguez-Pérez, J., Lozano-Fernández, I., López-Polín, L., Moreno, E., Vergès, J.M., Expósito, I., Agustí, J., Carbonell, E., Capdevila, R., & Vallverdú, J. (2015). Estudio preliminar de las tafofacies del pleistoceno inferior del yacimiento de El Forn (Barranc de la Boella, Tarragona, España). In: J.P. Galve, J. M. Azañón, & J. V Pérez Peña (Eds.), Una Visión Global Del Cuaternario. El Hombre Como Condicionante de Procesos Geológicos (pp. 46–48). Granada.

Sakellariou, D., & Galanidou, N. (2017). *Aegean Pleistocene landscapes above and below sea-level: Palaeogeographic reconstruction and hominin dispersals*. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-53160-1

Saladié, P., Vallverdú, J., Bennàsar, L., Cabanes, D., Mancha, E., Menéndez, L., Blain, H., Ollé, A., Mosquera, M., Vilalta, J., Cáceres, I., Expósito, I., Esteban, M., Huguet, R., Rosas, A., Solé, A., López-Polín, L., García, A. B., Martínez, B., … Capdevila, R. (2008). Resultats preliminars del Nivell 2 del sondeig al Centre de Convencions de la Boella-. *Cota Zero, 23*, 13–19.

Sánchez-Yustos, P., Diez-Martín, F., Domínguez-Rodrigo, M., Duque, J., Fraile, C., Baquedano, E., & Mabulla, A. (2017a). Diversity and significance of core preparation in the Developed Oldowan technology: Reconstructing the flaking processes at SHK and BK (Middle-Upper Bed II, Olduvai Gorge, Tanzania). *Boreas, 46*, 874–893. https://doi.org/10.1111/bor.12237

Sánchez-Yustos, P., Diez-Martín, F., Domínguez-Rodrigo, M., Duque, J., Fraile, C., Díaz, I., de Francisco, S., Baquedano, E., & Mabulla, A. (2017). The origin of the Acheulean. Techno-functional study of the FLK W lithic record (Olduvai, Tanzania). *PLoS One, 12*, e0179212. https://doi.org/10.1371/journal.pone.0179212

Santagata, C., Moncel, M.-H., & Piperno, M. (2020). Bifaces or not bifaces? Role of raw materials in the Middle Pleistocene. The example of levels E-E1, B and F (610–670 ka) at Notarchirico (Italy). *Journal of Archaeological Science: Reports, 33*, 102544. https://doi.org/10.1016/j.jasrep.2020.102544

Santonja, M., Pérez-González, A., Panera, J., Rubio-Jara, S., & Méndez-Quintas, E. (2016). The coexistence of Acheulean and Ancient Middle Palaeolithic techno-complexes in the Middle

Pleistocene of the Iberian Peninsula. *Quaternary International, 411*, 367–377. https://doi.org/10.1016/J.QUAINT.2015.04.056

Semaw, S., Rogers, M.J., Cáceres, I., Stout, D., & Leiss, A.C. (2018). The Early Acheulean ~1.6–1.2 Ma from Gona, Ethiopia: Issues related to the emergence of the Acheulean in Africa. In: R. Gallotti, & M. Mussi (Eds.), The Emergence of the Acheulean in East Africa and Beyond: Contributions in Honor of Jean Chavaillon (pp. 115–128). Springer International Publishing. https://doi.org/10.1007/978-3-319-75985-2_6

Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika, 52*, 591–611. https://doi.org/10.1093/biomet/52.3-4.591

Sharon, G. (2009). Acheulian giant-core technology. *Current Anthropology, 50*, 335–367. https://doi.org/10.1086/598849

Shipton, C., & Clarkson, C. (2015a). Handaxe reduction and its influence on shape: An experimental test and archaeological case study. *Journal of Archaeological Science: Reports, 3*, 408–419. https://doi.org/10.1016/j.jasrep.2015.06.029

Shipton, C., & Clarkson, C. (2015b). Flake scar density and handaxe reduction intensity. *Journal of Archaeological Science: Reports, 2*, 169–175. https://doi.org/10.1016/j.jasrep.2015.01.013

Silva-Gago, M., Ioannidou, F., Fedato, A., Hodgson, T., & Bruner, E. (2022). Visual attention and cognitive archaeology: An eye-tracking study of Palaeolithic stone tools. *Perception, 51*, 3–24. https://doi.org/10.1177/03010066211069504

Spearman, C. (1904). The proof and measurement of association between two things. *American Journal of Psychology, 15*, 72. https://doi.org/10.2307/1412159

Stiles, D. (1980). Industrial taxonomy in the Early Stone Age of Africa. *L'anthropologie, 18*, 189–207.

Stiles, D. (1991). Early hominid behaviour and culture tradition: Raw material studies in Bed II Olduvai Gorge. *The African Archaeological Review, 9*, 1–19. https://doi.org/10.1007/BF01117214

Stout, D. (2011). Stone toolmaking and the evolution of human culture and cognition. *Philosophical Transactions of the Royal Society of London. Series B, 366*, 1050–1059. https://doi.org/10.1098/rstb.2010.0369

Stout, D., Hecht, E., Khreisheh, N., Bradley, B., & Chaminade, T. (2015). Cognitive demands of lower Paleolithic toolmaking. *PLoS ONE, 10*, e0121804. https://doi.org/10.1371/JOURNAL.PONE.0121804

Terradillos-Bernal, M., & Rodríguez-Álvarez, X. P. (2014). The influence of raw material qualities in the lithic technology of Gran Dolina (units TD6 and TD10) and Galería (Sierra de Atapuerca, Burgos, Spain): A view from experimental archeology. *Comptes Rendus Palevol, 13*, 527–542. https://doi.org/10.1016/j.crpv.2014.02.002

Terradillos-Bernal, M., & Rodríguez-Álvarez, X. P. (2017). The influence of raw material quality on the characteristics of the lithic tool edges from the Atapuerca sites (Burgos, Spain). *Quaternary International, 433*, 211–223. https://doi.org/10.1016/j.quaint.2015.10.122

Tixier, J. (1957). Le hachereau dans l'Acheuléen nord-africain. Notes typologiques, in: Congrès Préhistorique de France. Comptes Rendus de La XVe Session (1956) (Paris: Bureau de La SPF). pp. 914–923.

Toro-Moyano, I., Barsky, D., Cauche, D., Celiberti, V., Grégoire, S., Lebegue, F., Moncel, M. H., & de Lumley, H. (2011). The archaic stone tool industry from Barranco León and Fuente Nueva 3, (Orce, Spain): Evidence of the earliest hominin presence in southern Europe. *Quaternary International, 243*, 80–91. https://doi.org/10.1016/j.quaint.2010.12.011

Tourloukis, V., & Harvati, K. (2018). The Palaeolithic record of Greece: A synthesis of the evidence and a research agenda for the future. *Quaternary International, 466*, 48–65. https://doi.org/10.1016/j.quaint.2017.04.020

Vallverdú, J., Saladié, P., Bennàsar, L., Cabanes, D., Mancha, E., Menéndez, L., BLain, H., Ollé, A., Vilalta, J., Mosquera, M., Cáceres, I., Expósito, I., Esteban, M., Huguet, R., Rosas, A., Solé, A., López-Polín, L., Martinell, J., Barbo, A., Martínez-Navarro, B., Agustí, J., Ros, S., Carbonell, E., & Capdevila, R. (2008). El barranc de la Boella de la Canonja (Tarragonès) revisitat en la intervenció arqueològica preventiva de l'any 2007. Trib. d'Arqueologia 7–28.

Vallverdú, J., Saladié, P., Rosas, A., Mosquera, M., Huguet, R., Cáceres, I., García-Tabernero, A., Estalrrich, A., Lozano-Fernández, I., Villalta, J., Esteban-Nadal, M., Benàssar, M. L., Pineda-Alcalá, A., Carrancho, Á., Villalaín, J. J., Bourlès, D., Braucher, R., Lebatard, A., Ollé, A., … Carbonell, E. (2014). Age and date for early arrival of the Acheulian in Europe (Barranc de la Boella, la Canonja, Spain). *PLoS One, 9*, e103634.

Vallverdú, J., Saladié, P., Rosas, A., Huguet, R., Cáceres, I., Pineda, A., Ollé, A., Mosquera, M., García-Tabernero, A., Estalrich, A., Carrancho, A., Villalaín, J., Bourlès, D., Braucher, R., Lebatard, A., Vilalta, J., Lozano, I., López-Polín, L., Moreno, E., … Capdevila, R. (2014a). El Barranc de La Boella (La Canonja, Tarragona, Catalonia, Spain). In R. E. Sala (Ed.), *Pleistocene and Holocene hunter-gatherers in Iberia and the Gibraltar Strait: The current archaeological record* (pp. 287–295). Universidad de Burgos.

Vaquero, M. (1997). *Tecnología lítica y comportamiento humano: Organización de las actividades técnicas y cambio diacrónico en el Paleolítico Medio del Abric Romaní (Capellades, Barcelona)*. Universitat Rovira i Virgili.

Vaquero, M. (1999). Variabilidad de las estrategias de talla y cambio tecnológico en el Paleolítico Medio del Abric Romaní (Capellades, Barcelona). *Trabajos De Prehistoria, 56*, 37–58.

Viallet, C., De Weyer, L., Ivorra, J., Rios-Garaizar, J., Barsky, D., Cuartero, F., Bello-Alonso, P., & Bourguignon, L. (2022). Du macro-outillage tranchant utilisé en percussion lancée dans les premières phases de l'Acheuléen européen ? Le cas de l'US4 de Bois-de-Riquet (Lézignan-la-Cèbe, Hérault, France). *Comptes Rendus Palevol, 21*, 175–189. https://doi.org/10.5852/CR-PALEVOL2022V21A8

Villa, P. (2001). Early Italy and the colonization of Western Europe. *Quaternary International, 75*, 113–130. https://doi.org/10.1016/S1040-6182(00)00083-5

Wynn, T. (2002). Archaeology and cognitive evolution. *The Behavioral and Brain Sciences, 25*, 389–402. https://doi.org/10.1017/S0140525X02000079

Yravedra, J., Courtenay, L. A., Gutiérrez-Rodríguez, M., Reinoso-Gordo, J. F., Saarinen, J., Égüez, N., Luzón, C., Rodríguez-Alba, J. J., Solano, J. A., Titton, S., Montilla-Jiménez, E., Cámara-Donoso, J., Herranz-Rodrigo, D., Estaca, V., Serrano-Ramos, A., Amorós, G., Azanza, B., Bocherens, H., DeMiguel, D., … Jiménez-Arenas, J. M. (2024). Not seen before Unveiling depositional context and Mammuthus meridionalis exploitation at Fuente Nueva 3 (Orce, southern Iberia) through taphonomy and microstratigraphy. *Quaternary Science Reviews, 329*, 108561. https://doi.org/10.1016/j.quascirev.2024.108561

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Diego Lombao[1,2,3] · **Juan I. Morales**[2,4] · **Marina Mosquera**[2,4] · **Andreu Ollé**[2,4] · **Palmira Saladié**[2,4,5] · **Josep Vallverdú**[2,4,5]

✉ Diego Lombao
diego.lombao@gmail.com; diego.lombao@usc.es

1 GEPN-AAT, Dpto. Historia, Facultade de Xeografía e Historia, USC, Praza da Universidade 1, 15782 Santiago de Compostela, Spain

2 Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), Zona Educacional 4, Campus Sescelades URV (Edifici W3), 43007 Tarragona, Spain

3 UMR7194 Histoire Naturelle de L'Homme Préhistorique (HNHP), Museum National d'Histoire Naturelle (MNHN), CNRS, Université Perpignan Via Domitia, Alliance Sorbonne Université, - Musée de L'Homme, Place du Trocadéro 17, 75016 Paris, France

4 Universitat Rovira i Virgili, Departament d'Història i Història de L'Art, Avinguda de Catalunya 35, 43002 Tarragona, Spain

5 Unit Associated to CSIC, Departamento de Paleobiología, Museo Nacional de Ciencias Naturales (MNCN), Consejo Superior de Investigaciones Científicas (CSIC), Calle José Gutiérrez Abascal 2, 28006 Madrid, Spain