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The Western European Acheulean: Reading variability at a regional scale

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ABSTRACT

In the context of the Western European Acheulean Project, this study aims to characterize Acheulean technology in Western Europe through the analysis of handaxes and cleavers from 10 key sites (Britain 4, France 4, and Spain 2) to acquire a regional view of the occupation. The historically different systems used to categorize and analyze the data have made it difficult to compare results. Here we apply a unified and simple method (Western European Acheulean Project) that combines the traditional technological and metrical analysis of assemblages containing handaxes and cleavers with an in-depth geometric morphometric approach using three-dimensional models. This approach allows us to achieve a regional interpretation that identifies innovations through time and shaping strategies across the area. Our findings indicate the existence of two main technological groups in the sampled record: 1) northwestern and central France and Britain, from MIS 17/16 to MIS 11, and 2) Atlantic edge (Atapuerca in Spain and Menez-Dregan in France), from MIS 12/11 to MIS 8. Based on our technological analysis, the shaping of handaxes and cleavers was developed through time as a continuum of accumulative actions, with longer and more complex shaping strategies over time. Shaping technology shows traditions of manufacture over both time and geographical areas, which suggest cultural diffusion. Our geometric morphometric analysis further helped to identify not only general trends but also local adaptations in handaxe forms. Based on our findings, there were no apparent sudden innovations, but rather the application and development of specific techniques to refine size and shape.

1. Introduction

The earliest human dispersals into Western Europe appear to have occurred ca. 1 Ma. A 'source and sink' model was proposed based on the latest results from DNA data on the Atapuerca-Sima de los Huesos fossils (Martinón-Torres et al., 2018), where variation in hominin samples in the European Early and Middle Pleistocene was explained as a result of repeated population dispersals, fragmentation, and recombination of surviving populations within Europe (Dennell et al., 2011). Sources mainly referred to refugia in southern latitudes or coastal areas during glacial periods where climatic conditions remained relatively mild and tolerable for survival (Dennell et al., 2011; MacDonald et al., 2012; Bermúdez de Castro et al., 2013a, 2013b). Therefore, climate (i.e., glacial-interglacial cycles) was the main force constraining the expansion and settlement of hominins in Europe (Carrión et al., 2011; Dennell et al., 2011; Antoine et al., 2019; Blain et al., 2021), with hominins using south-north corridors of dispersal, particularly in the more oceanic regions of Western Europe (Parfitt et al., 2010; Ashton and Lewis, 2012; Mosquera et al., 2013).

Our knowledge of early human behavior relies heavily on stone tools and the technological strategies they display (Key, 2019). In particular, the Middle Pleistocene period is characterized by Lower Paleolithic assemblages, including the Acheulean technocomplex.

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Handaxes are considered as one of the main innovations of the Acheulean, alongside the production of cleavers and large flakes. These tools, together with other technological and behavioral developments (e.g., core technologies, bone and wood working, land-use patterns, hunting), have profound cognitive implications (Isaac, 1969, 1986; Stout, 2011). Handaxe manufacture entails planning and a hierarchical organization of activities that may be fragmented and therefore show an understanding of space and time (Wynn, 1989; Toth, 1991). In addition, handaxe shaping implies demands on the working memory to mentally rotate objects (Stout, 2015), consistent with the marked increase in brain size observed in early *Homo erectus* (Antón, 2003). The continuous presence of these types of tools through the chronological time frame presented within this paper (MIS 17/16—MIS 8) allows us to track human presence and strategies across the European landscape.

Handaxes and cleavers have also contributed important evidence for identifying cultural regions through their mode of shaping and morphological end-forms (Roche, 2005; Gowlett, 2006). The effectiveness and apparent versatility of these tools are crucial factors in their persistence over more than 1.5 Myr and over a vast geographical area (Clark, 1994; Moncel et al., 2018). However, despite the apparent stability of the Acheulean shown by the persistent presence of handaxes, understanding the significance of this technocomplex variability continues to be a major research theme. The challenges include distinguishing common shaping strategies that have cultural meaning from those resulting from convergent evolution, and/or identifying new technologies through space and time. In Europe, for example, Schreve et al. (2015) recognized common technological features, suggesting possible affiliation of populations before and after the MIS 12 glaciation. Equally, there appear to be technological innovations through this period, so understanding the process of innovation is critical for assessing internal developments or external introduction. Renfrew (1978) distinguished between invention and innovation, whereby the former is the creative act that is usually invisible in the archaeological record, whereas the latter is the long-term establishment of the creative act. Sudden innovation is more likely to indicate external introduction, while smaller increments of change suggest internal implementation through technological development, cognitive evolution, or acculturation (Moncel et al., 2021).

The aim of this paper is to explore the spatial and chronological variation in handaxe and cleaver technology and morphology to understand human population dispersal in Western Europe. This goal is approached through the study of 10 key sites from ca. 700 ka (MIS 17/16) to ca. 250 ka (MIS 8/7) from Spain, France, and Britain (Fig. 1). Using a unified methodological approach to understand the variability of the Acheulean, we aim to distinguish common shaping strategies and identify new shaping techniques, allowing a better understanding of the origin and evolution of traditions of practice. This overarching aim is addressed through the following four main research questions (RQs):

1. Are there statistically significant geographical patterns between sites in the data?
2. Are there statistically significant chronological patterns between sites in the data?
3. If chronological patterns can be identified, are they suggestive of innovations by new populations, or in situ regional development of technology?
4. If geographical patterns can be identified, are there noncultural factors, such as raw material differences, that might explain the variation?

There are two main practical considerations for any study of European handaxe and cleaver variability. In Western Europe, different traditions of Lower Paleolithic research have hindered inter-regional comparisons. Following the earlier metrical approaches of Bordes (1961) and Roe (1968), the ‘chaîne opératoire’ was developed in France in the 1980s (Pelegrin, 1986; Pelegrin et al., 1988; Boëda et al., 1990; Soressi and Geneste, 2011; Monnier and Missal, 2014; Delage, 2017; Baena et al., 2018; Pope et al., 2020), related processual approaches were developed in Britain (Newcomer, 1971; Wenban-Smith, 1989; Ashton and McNabb, 1994; McPherron, 1995; White, 1998a, 1998b; Emery, 2010), and the Logical Analytical System was developed in Spain (Carbonell et al., 1983, 1995b; Ollé et al., 2013; García-Medrano et al., 2014, 2019; Mosquera et al., 2018). These various analytical systems across Europe have led to problems when attempting to compare results between sites. We address this problem here through the use of the Western European Acheulean Project (WEAP) method, a unified, simple, and flexible system, applicable to all of the sites, that enables inter-regional comparisons (García-Medrano et al., 2020a, 2020b; see below).

A further problem has been varied assemblage formation (e.g., primary/secondary context, open-air/cave situations) and recovery history (e.g., collection/excavation). Many of the larger assemblages of handaxes come from historic collections from secondary fluvial contexts, in contrast to often smaller assemblages from recent excavation. For this study, it has been important to formulate questions that are appropriate to the data and optimize assemblage size with good age constraint by use of historic collections. The bias toward handaxes (over cores, flakes, etc.) in historic collections means that complete assemblages cannot be studied but provides some assurance that handaxes are representative of each site. Additionally, secondary context assemblages, such as river terrace gravels, provide a ‘time-averaged’ body of data that should be representative of landscape use over a defined time. These contrast with time-limited or space-limited events in primary context sites or caves. These potential problems are fully considered in the Supplementary Online Material (SOM).

2. Materials and methods

2.1. Materials: Middle Pleistocene sites

Although there is a large number of Lower Paleolithic sites, assemblages, and artifacts from Western Europe, there are comparatively few assemblages that comprise sufficient numbers of handaxes and cleavers with secure contexts, and that can be attributed with some certainty to a marine isotope stage. To address our four RQs, 10 sites were carefully selected that cover the geographical and chronological range. They comprise 397 handaxes and cleavers from 15 assemblages with a geographical spread from Atapuerca in Northern Spain to Brandon Fields in the United Kingdom (Fig. 1).

For the smaller assemblages, all available complete handaxes and cleavers were studied. For the larger assemblages (Brandon Fields, Boxgrove, Swanscombe, and la Noira), each assemblage was visually inspected in its entirety, and boxes (each holding 2–6 handaxes) were selected that appeared representative of the full range.

The chronological range includes two major glaciations that may have led to depopulation in Northern Europe during MIS 16 and MIS 12 (Ashton and Lewis, 2012; Moncel et al., 2015; Hosfield, 2016). This range provides an overall framework for understanding connections and disconnections through time and space. One of the

Figure 1. Location of the sites included in the paper: Brandon Fields, Boxgrove, Swanscombe-UMG, Elveden, la Noira (including strata a and c), Menez-Dregan, Saint-Pierre-lès-Elbeuf, Cagny-la-Garenne, including Lower Level (Ca) and Upper Levels (Cxb, Cxv); Atapuerca includes Galería (GIIa, GIIb, GIIIa, GIIIb subunits) and Gran Dolina (TD10.1). Black dots are other Acheulean sites not considered in this study. Map from: https://www.esa.int/var/esa/storage/images/esa_multimedia/images/2018/04/cloud-free_europe/17486453-1-eng-GB/Cloud-free_Europe.jpg. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

challenges of this type of study is the different dating resolutions between the various sites (cf. Bridgland et al., 2006; Nicoud, 2013; Voinchet et al., 2015; Davis and Ashton, 2019). British assemblages present a relative chronology with, at times, high precision. The combination of glacial history, its relationship with terrace stratigraphy, good preservation of biological remains, and the wide deployment of aminostratigraphy has provided a good resolution to the dating and enabled correlation between sites and the Marine Isotope record (Ashton, 2016). By contrast, the chronology of French sites relies more on radiometric dating and well-documented terrace stratigraphies. In the past decade, absolute dating methods have been widely applied to several sites such as la Noira (Despriée et al., 2011) and Menez-Dregan (Mercier et al., 2004). Atapuerca is different, with a large series of absolute dates relying on different methods, leading to contradictions between some of them (Ollé et al., 2016). Despite the different dating methods and geological frameworks, all the sites in this study can be attributed to MIS, and it is this level of chronological resolution that is used in this paper to analyze and interpret the regional pattern. Below we introduce the 10 sites used in this analysis.

Brandon Fields An undulating surface of small gravel pits on a hilltop south-west of Brandon, Suffolk (UK), marks the site of Brandon Fields (BF), from which 148 handaxes were collected, predominantly in the late 19th century (Flower, 1869; Evans, 1872). Flower provided a clear location and description of the geology, which has been verified through recent fieldwork (Davis et al., 2021). The gravel forms part of the Timworth Terrace of the Bytham River and is attributed to MIS 14 (Lewis et al., 2021). Analysis of the condition of the collection indicates different taphonomic histories. About 85% of the handaxes are rolled and stained, probably deriving from MIS 15 land surfaces (see Davis et al., 2021). There is a much smaller, less rolled, and patinated component that probably originates from the terrace surface and may date to MIS 13. In a small number of cases, it is not quite clear to which component they belong. There are 137 handaxes in the British Museum collections, of which 50 were selected for this study, attributed to MIS 15. The raw material is exclusively local flint, usually in the form of medium- to large-sized river cobbles or nodules (Table 1).

Boxgrove—Q1B Located in Sussex (UK) on an ancient coastline, Boxgrove (BOX) consists of a sequence of early Middle Pleistocene marine, freshwater, and terrestrial sediments exposed in the former Eartham Quarry. The units were formed within a semi-enclosed marine embayment at the onset of marine regression (Roberts and Pope, 2009, 2018). The site has been attributed based on mammalian biostratigraphy to the last temperate stage of the Cromerian Complex, MIS 13 (524—478 ka; Roberts and Parfitt, 1999). Cold stage sediments overlying the temperate sequence and transitional mammalian faunas suggest that the main archaeological horizons date to the final part of the interglacial just before the ensuing Anglian Cold Stage (MIS 12; Roberts and Parfitt, 1999; Roberts and Pope, 2018). The lithic collection is exceptional in terms of the density of knapping scatters, including complete shaping sequences. The main handaxe assemblage is from the Q1B watering hole with more than 400 handaxes, from which 49 were recorded for this study. The raw material is large nodules of flint that had been freshly eroded from the adjacent chalk cliff (Table 1).

Elveden The old clay pit at Elveden (ELV), Suffolk (UK), has been known since the late 19th century, with excavations in 1937 and from 1995 to 1999 (Paterson and Fagg, 1940; Ashton et al., 2005). Fine-grained lacustrine and fluvial sediments formed in a small basin on Anglian (MIS 12) till and date to the Hoxnian interglacial (MIS 11c; Ashton et al., 2005). The main handaxe assemblage was collected in the early 20th century with additional material from the two excavations. The excavated assemblages were recovered from the edges of the lacustrine deposits, often associated with a lag gravel. The wide range of surface patination, staining, and overall fresh condition is very similar to those from the collected assemblage, supporting the interpretation that they all come from the same set of deposits. Instances of refitting and the fresh condition of the artifacts indicate that they are in primary context. In total, 80 handaxes have been recorded from the site and held in several different museums. For this research, all 29 handaxes in the British Museum collection were studied, including three from the 1990s excavations. The raw material consists of local river cobbles and nodules eroded out from nearby chalk (Table 1).

Swanscombe—Upper Middle Gravels The former gravel quarry pit of Barnfield Pit, Swanscombe (SW) is located on the Orsett Heath terrace of the River Thames in Kent (UK). The fluvial sediments (Stages I and II) are attributed to the Hoxnian interglacial (MIS 11c; Conway et al., 1996; White et al., 2013). The Stage I deposits contain non—handaxe assemblages and date to the first half of the interglacial, while the handaxe assemblages from the Stage II deposits date to the second part of the interglacial. The Stage II deposits are divided into the Lower Middle Gravels and the Upper Middle Gravels (UMG). For this study, we used the only excavated assemblage from the Wymer 1950s excavations of the UMG, which was associated with the Swanscombe skull (Ovey, 1964). The assemblage is in secondary context but was probably derived from the nearby floodplain of the river, using local flint gravels as the source for raw material (Moncel et al., 2015). For this study, 49 handaxes were sampled from a total of 143. The raw material consists of local, generally medium-sized river cobbles (Table 1).

La Noira This site is located in the Middle Loire Basin (Centre region, France). Five successive strata have been defined with two archaeological assemblages. The basal layer (stratum a, LN.a) was deposited after river incision at the beginning of a glacial stage, which, with electron spin resonance (ESR) dating, has been attributed to the MIS 17/16 transition (Voinchet et al., 2010; Despriée et al., 2011; Moncel et al., 2013). The Upper Level (stratum c, LN.c), with a date of 449 ± 45 ka, overlies an erosive surface with truncated ice wedges, suggesting that the associated artifacts were probably discarded during a temperate phase, late MIS12/early MIS11 (Iovita et al., 2017). A total of 105 handaxes were excavated, from which the entire assemblage of 31 handaxes was studied from stratum a, and 47 from stratum c. All the knapping in stratum a was on blocks or slabs of local siliceous millstone. For stratum c, half of the handaxes were made on local millstone while others were made on imported flint (Table 1).

Cagny-la-Garenne The site is located in fluvial deposits of the Middle Terrace of the Somme Valley (France), which, based on the geological framework of the Somme, has been attributed to the beginning of MIS 12, with ESR dates of 400 ± 101 ka (Antoine et al., 2007). The excavations were in two main areas, referred to as Cagny-la-Garenne (CLG) 1 and 2. In this study, we focused on Cagny-la-Garenne 1 as it has the largest quantity of handaxes and is

Table 1

Handaxes and cleavers by sites and raw materials considering five main categories: chert and flint (including all flint varieties and sedimentary rocks with micro- or cryptocrystalline grain, e.g., millstone slabs from la Noira), quartzite and quartz (including filonian quartz and the complete set of metamorphic rocks with high quartz content), other metamorphic rocks (i.e., schist, hornfels, sandstone, metasandstone), and limestone.

	Sites	MIS	(*n*)	Handaxe	Cleaver	Chert/flint	Millstone	Quartzite/quartz	Other metamorphic rocks	Limestone
Britain	BF	MIS 16	50	50	–	50	–	–	–	–
	BOX	MIS 13	49	49	–	49	–	–	–	–
	SW	MIS 11	49	49	–	49	–	–	–	–
	ELV	MIS 11	29	29	–	29	–	–	–	–
France	LN.a	MIS 17/16	31	31	–	–	31	–	–	–
	LN.c	MIS 12	47	47	–	24	23	–	–	–
	MD	MIS 11	20	16 (80%)	4 (20%)	–	–	6	14	–
	SP	MIS 11	8	8	–	8	–	–	–	–
	CLG.L	MIS 12	14	14	–	14	–	–	–	–
	CLG.U	MIS 11	18	18	–	18	–	–	–	–
Iberian Peninsula	GIIa	MIS 12/11	13	9 (70%)	4 (30%)	3	–	7	3	–
	GIIb	MIS 8/7	17	9 (53%)	8 (47%)	6	–	5	5	1
	GIIIa	MIS 8/7	13	11 (85%)	2 (15%)	2	–	4	7	–
	GIIIb	MIS 8/7	11	11	–	4	–	3	4	–
	TD10.1	MIS 10/8	28	23 (83%)	5 (17%)	11	–	7	10	–
Total			**397**	**374 (94.21%)**	**23 (5.79%)**	**267**	**54**	**37**	**43**	**1**

Abbreviations: BF = Brandon Fields; BOX = Boxgrove; SW = Swanscombe-UMG; ELV = Elveden; LN.a = la Noira stratum a; LN.c. = la Noira stratum c; MD = Menez-Dregan; SP = Saint-Pierre-lés-Elbeuf; CLG.L = Cagny-la-Garenne Lower Level (Ca); CLG.U = Cagny-la-Garenne Upper Levels (Cxb, Cxv); GIIa, GIIb, GIIIa, GIIIb = Galería, Atapuerca; TD10.1 = Gran Dolina, Atapuerca.

directly dated. This part of the site is composed of fluvial silts interstratified with chalky sediments, and from which six artifact assemblages were excavated in 1986 (Lamotte, 1999; Lamotte and Tuffreau, 2001a, 2001b; Tuffreau and Lamotte, 2010). The site was interpreted as a workshop where local, large flint nodules were used to manufacture bifaces, cores, flakes, notches, and denticulates. For this study, all the complete 32 handaxes were sampled from Series Ca (14) and Series Cxb/Cxv (18), with only one handaxe made on a flake (Table 1).

Menez-Dregan The site of Menez-Dregan (MD) on the coast of the Armorican Massif (Finistère, France) is an ancient marine cave where the roof progressively collapsed, partially protecting the archaeological living floors (Monnier, 1996; Mercier et al., 2004; Ravon et al., 2016a, 2022; Ravon, 2018). The site has an alternating sequence of levels of human occupation and marine deposits dated between ca. 465 and 113 ka. In this study, we focus on Layers 8 and 7, dated to MIS 11 and 10 (Mercier et al., 2004), which are interpreted as residential locations. Only 20 handaxes and cleavers were recovered from these levels, all of which were studied for this research. They were nearly all made on flakes knapped from local beach cobbles of sandstone, quartzite, microgranite, and quartz (Table 1).

Saint-Pierre-lès-Elbeuf The site of Saint-Pierre-lès-Elbeuf (SP) is located in the Seine Valley (France), where four loess layers are interspersed with four interglacial soils: Elbeuf I (Eemian) to Elbeuf IV. The oldest soil (Elbeuf IV) is probably attributable to MIS 11 (Cliquet et al., 2009), and is immediately overlain by white alluvial sands with faunal and lithic remains, which are in secondary context. It is also covered by a limestone tufa, attributed to MIS 10 (Cliquet et al., 2009). Recent fieldwork has investigated the white sands and tufa. One area of 45 m^2 yielded in situ Acheulean artifacts and faunal remains (Cliquet et al., 2009), while rolled artifacts and bones in secondary context were recovered from another area at the same level. From the old and new collections, two occupation phases have been identified from below and above the tufa (Moncel et al., 2015). Only eight handaxes can be attributed with any certainty to these levels, and all were included in the current study. They were all made on local flint (Table 1).

Galería The Galería complex (GIIa, GIIb, GIIIa, GIIIb) is located on the western side of the Sierra de Atapuerca (Spain). Five main infilling phases were distinguished but only GII and GIII are archaeo-paleontological deposits. Several dating methods have been used, providing a series of dates between MIS 11 and MIS 8 (Aguirre, 2001; Falguères et al., 2001, 2013; Berger et al., 2008; Demuro et al., 2014; Arnold and Demuro, 2015). Two human fossils were recovered at Galería (TZ area), an adult mandible fragment with two molars (Bermúdez de Castro and Rosas, 1992) and an adult neurocranial fragment (Arsuaga et al., 1999). Taphonomic analysis suggests that the cave was mostly water-logged and in semi-darkness during the time of hominin occupation, while the lithic assemblages also suggest limited domestic activities. The preferred interpretation is that hominins visited the site sporadically to retrieve animal carcasses that had fallen through a natural cave shaft and were in direct competition with carnivores for these resources (Díez and Moreno, 1994; Huguet et al., 2001; Ollé et al., 2005; Cáceres et al., 2010). According to this model, Galería would have been a 'complementary settlement area' in the complex karst network of Atapuerca where hominins made occasional visits (Carbonell et al., 1995a, b; Ollé et al., 2013; García-Medrano et al., 2014, 2017). All 54 handaxes and cleavers that had been recovered up to 2013 were studied from GIIa, GIIb, GIIIa, and GIIIb. The raw materials were predominantly chert followed by sandstone, including sandy schist and metasandstone, quartzite, with rare use of quartz (Table 1).

Gran Dolina The site of Gran Dolina (TD) is also a cave in the Sierra de Atapuerca, ca. 50 m north of Galería. TD10.1 is one of the richest levels at Atapuerca, yielding 48,000 faunal remains and more than 20,000 artifacts (Ollé et al., 2013; García-Medrano et al., 2015; de Lombera-Hermida et al., 2020). There is one average ESR/uranium-thorium (U—Th) date for the top of the sequence (337 ± 29 ka, Upper TD10.1) and one direct ESR/U-Th date for the 'bone-bed level' (Lower TD10.1), yielding a value of 379 ± 57 ka (Falguères et al., 1999), although optically stimulated luminescence results point to a slightly younger age (Berger et al., 2008). The base of TD10.1 was interpreted as the result of repeated, high-intensity residential occupations (base camps; Rodríguez-Hidalgo et al., 2015; López-Ortega et al., 2017; Pedergnana and Ollé, 2020). In the middle part of this subunit, humans may have alternated high-intensity, long-term occupations with sporadic, short-term ones (Rosell, 2001; Blasco et al., 2013a, b). In the uppermost layers, the assemblages are interpreted as the result of repeated, low-intensity, and short-term occupation (Ollé et al., 2013; Saladié et al., 2018). All 28 handaxes and cleavers from Gran Dolina TD10.1 were recorded in the current study. The raw materials were the same as Galería with a mix of local chert, sandstone, and quartzite (Table 1).

2.2. Methods of analysis

Data collection There has been long and extensive discussion, still ongoing, about the nomenclature of large Acheulean tools (de Mortillet, 1873; Kleindienst, 1962; Isaac, 1968; Roe, 1994, 2006; Debénath and Dibble, 1994; Deacon and Deacon, 1999; Noll, 2000; Sharon, 2007, de la Torre, 2016). For this study, we limit the terms to handaxe and cleaver. For handaxes, we use the definition of Kleindienst (1962) as a tool characterized by an all-round cutting-edge, but sometimes with the exclusion of the butt. These are normally bilaterally symmetric and generally biconvex. Cleavers are particularly prevalent in Southern Europe, Africa, the Levant, and India, but have various definitions. In Iberia, cleavers are broadly defined technologically as made on flakes or cobbles, sometimes with a retouched transverse edge (García-Medrano et al., 2014, 2015), while in Britain and France, they include bifacially knapped tools with a transverse cutting edge (i.e., bifacial cleavers of Bordes, 1961). To avoid confusion and help unify terminology, we use the broad definition noted earlier but distinguish between the 'true cleavers' of Tixier (1956) as tools made exclusively on flakes with an unretouched transverse cutting edge, and 'cleaver-like' tools that can be bifacially worked on cobbles or with retouched distal ends.

The WEAP method (see García-Medrano et al., 2020a) considers each handaxe or cleaver from two perspectives: as a single unit, and as the sum of the different morphofunctional parts (tip, midsection, butt), each of which is analyzed independently, combining qualitative and quantitative data (Table 2; Fig. 2). As a single unit, each tool can be defined by a combination of features that make it unique: raw material and blank type, facial working, edge delineation, bifacial and bilateral symmetry, and number of scars. The division of each tool into three parts is based on the metrical distinction of the distal part at one-fifth of length and the proximal part at four-fifth of length from the tip (Roe, 1968). Therefore, each technological analysis is undertaken three times. The technological features considered here are type of hammer (only identifiable on clear pieces), number of removal series, depth of scars on edges, invasiveness of scars on a tool's surface, type of shaping, and any patina variation.

Together with technological descriptions, measurements form the basis of Bordes' handaxe morphological types ('triangulaires,' 'subtriangulaires,' 'cordiformes,' discoid, ovate, and 'limandes' or

Table 2
Technological features considered in the analysis of handaxes and cleavers according to the WEAP method (García-Medrano et al., 2020a).

	WEAP method: Technological features	
	Large Cutting Tools as a single unit	
Variable	**Categories**	**Description**
Raw material	Type	Flint, chert, quartzite, quartz, limestone, and other metamorphic rocks
Blank type	Blocks	Broken from bedrock
	Nodules	Eroded from bedrock
	Cobbles	From river gravels
	Flakes	Detached from cobbles/nodules
Number of faces	Unifacial	Only one shaped face
	Bifacial	Two shaped faces
	Trifacial	Three shaped faces
Cortex localization	Tip	Cortex only on tip
	Mid	Cortex on mid part
	Butt	Cortex on butt part
	All	Cortex over the whole piece
Edge delineation	Straight	In profile view
	Sinuous	
	Curved	
Symmetry	SIM	Symmetric profile
	NSIM	Nonsymmetric profile
Number of scars	(*n*)	Counted per face
Large Cutting Tools for each morphofunctional part (tip, midsection, and butt)		
Variable	**Categories**	**Description**
Hammer used	Hard	Deep bulbar impressions, deep effect of scars on edge
	Soft	Minimal bulbar impressions, marginal effect of scars on edge
	Combined	Combination of both
Presence of cortex	%	
Removal series	1	One removal series
Add as many as needed	2	Two removal series
	3	Three removal series (or more)
	Final retouch	Could be a removal series by itself
	Combined	The combination of these series
Depth scars on edge	Deep	Generating denticulate edges
	Marginal	Creating continuous edges
Invasiveness (scars on tool's surface)	Noninvasive	Removals close to the edge
Analysis of each series of removals	Invasive	Removals affecting $\geq$50% of piece
Final retouch	Noninvasive	Removals close to the edge
	Invasive	Removals affecting $\geq$50% of piece
	Specific types	E.g., tranchet, shallow retouch
Type of shaping	General	According to the rest of tool's shaping strategy
	Specific	Different ways (e.g., combination of different series or with different depth or invasiveness).
	Final retouch	E.g., tranchet removals or shallow retouch

Abbreviation: WEAP, Western European Acheulean Project.

elongated ovates) according to three main criteria: length against width, thickness against width, and edge shape (Bordes, 1961). However, the boundaries between the categories were sometimes imprecise, as intermediate shapes exist. Roe (1968) included three new measures: distal width (B1), proximal width (B2), and distal thickness (T1), to distinguish three shapes: pointed, oval, and cleaver-type tools. We use all these measures to describe the tools (Fig. 2; Table 2) and to statistically compare the results with morphological and technical features such as reduction intensity. These measurements have also been used to produce ratios to enhance handaxe description. Here, elongation is given as length/width with values >1.5 described as elongated. Refinement is measured by width/thickness with refined handaxes having values >2.35 (Bordes, 1961; Roe, 1968, 1994). In addition to these basic measurements and ratios, we measured six angles along the most continuous and regular edge starting at A1 (midpoint of tip), A2 (1/5 of the length), A3 (2/5), A4 (3/5), A5 (4/5), and A6 (midpoint of butt). Where there is cortex, the angle was not recorded.

Technological and morphometrical data analysis To address RQ1 and RQ2, this large set of technological features was combined by applying a principal components analysis (PCA) to identify the differences and similarities of handaxes and cleavers across sites. Each principal component (PC) reflects a specific combination of technological features, complemented with biplots, as both complete tools and as three parts of a tool (tip, midsection, butt). The technological analysis also compared raw materials and types of blank. This PCA was combined with an average-linkage cluster analysis that considered the Euclidean distance between sites to quantify their differences or similarities. Nonparametric tests were used to test for differences among/between groups in the PCs. The Kruskal–Wallis (K–W) test was used to test for statistically significant median differences among three or more independent groups while the Mann–Whitney (M–W) U test (or Wilcoxon rank-sum test) was used to test for pairwise group differences in median values using PAST v. 3.14 software (Oslo University, Oslo). The alpha level of significance for these and all other statistical tests was set at 0.05.

We also applied geometric morphometrics (GM) on 3D models to analyze variation in tool shape. All the tools were scanned using a DLP projector laser scanner and FleXScan software v. 3.3.5.8. (LMI technologies, Burnaby) transferred from the Fragmented Heritage Project (University of Bradford), or a Breuckmann SmartScan and Optocat software v. 2012 R2-2206 (AICON 3D Systems GmbH, Surrey). All 3D models are available for scientific and academic purposes at ZENODO (García-Medrano, 2021). The 3D models were processed using the AGMT3-D software v. 3.1 (Herzlinger and

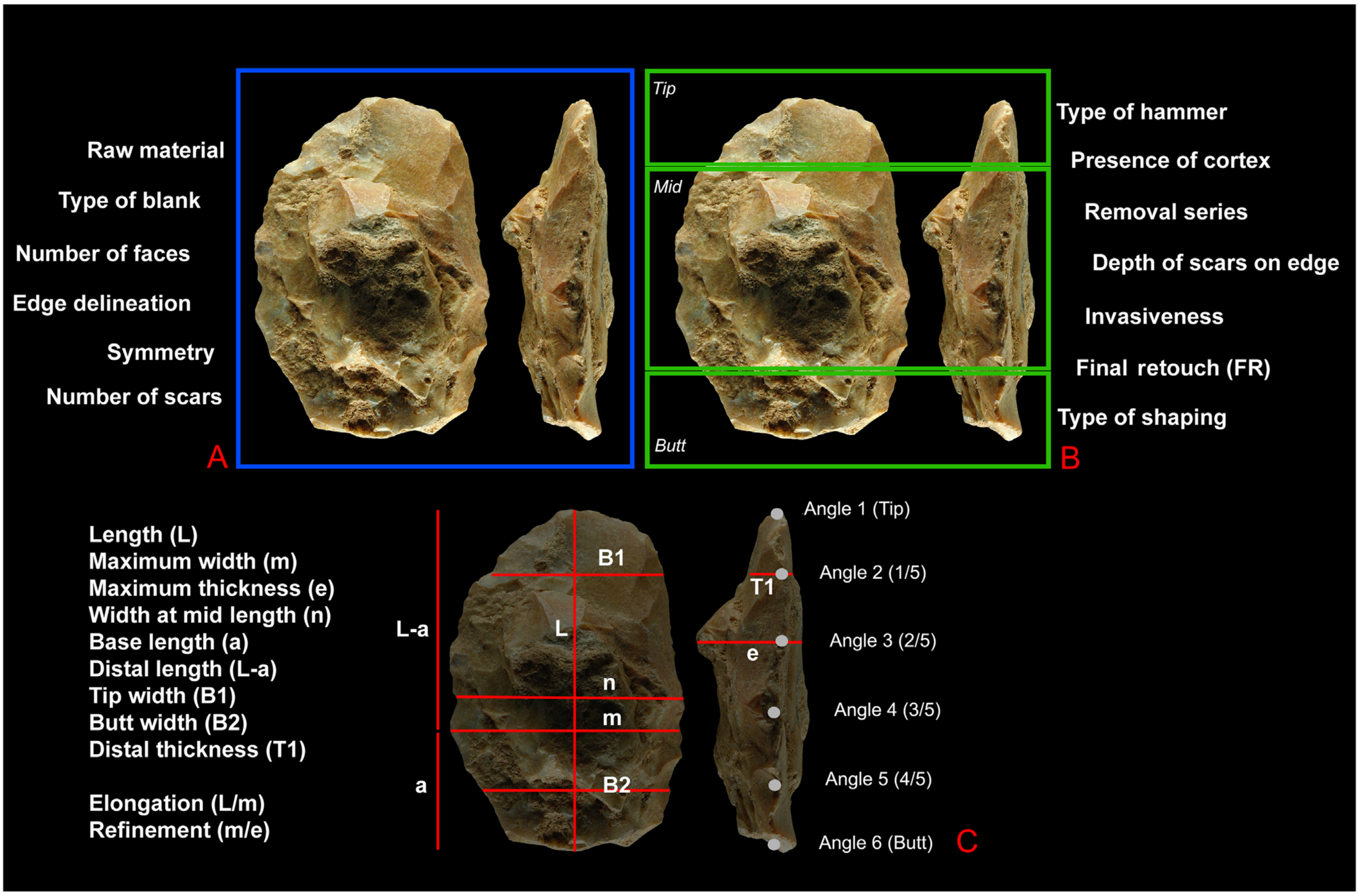

Figure 2. Technological features on each tool A) considering each tool as one unit, and B) divided into three parts: tip, midsection, and butt. Qualitative (A, B) and quantitative (C) features (linear dimensions, indices, and angles) are depicted (according to García-Medrano et al., 2020a). The example is a handaxe from stratum a of la Noira (BFLN_0A7_d2_1).

Grosman, 2018; Herzlinger and Goren-Inbar, 2020). We have excluded any fragmented tools without a complete morphology.

The software supports 3D models in VRML format (*.wrl files). Models should be watertight, i.e., they should have no holes or borders and should not contain any nonmanifold edges and vertices. Each file is read and the model is positioned following the protocol published by Herzlinger et al. (2017). First, the model is rotated in 3D according to the distribution of the normal vectors on its surface. Then, the model is rotated in 2D along the XY plain according to the maximal measured distance (i.e., maximal length). These two steps are automatically applied based on geometric criteria, thus providing an objective geometric basis for the semilandmark homology. Then, the user should confirm that all models are consistently positioned in terms of ventral/dorsal faces and proximal/distal ends (Fig. 3A). If they are not consistently positioned, the user can change the face orientation using the ‘Flip about Y’ button (Fig. 3B) and/or change the orientation of the ends using the ‘Rotate about Z’ button (Fig. 3C). While the ‘Flip about Y’ button performs 180° rotation (flipping), the ‘Rotate about Z’ button performs 90° rotations. This is for cases where distal/proximal symmetry is higher than the bilateral symmetry and therefore the automatic item planform positioning is incorrect (Herzlinger et al., 2017).

After all items have been visualized and their position confirmed, the software builds a 3D orthogonal grid on the surface of the object. Each point of the grid consists of two semilandmarks, one placed on each face of the artifact, so that a 50 × 50 grid provides 5000 semilandmarks (Fig. 4A). The top and bottom latitudes capture the exact 3D outline of the artifact's distal and proximal ends. Therefore, this protocol provides a list of semilandmarks that accurately reflect the artifact's volumetric configuration. The software also provides a number of analytical tools and procedures that enable data processing and statistical analysis (Herzlinger and Grosman, 2018).

The morphological data were subjected to a set of multivariate statistical procedures and analyses to detect and quantitatively describe shape differences within and between assemblages (Herzlinger and Goren-Inbar, 2019). The analysis included a generalized Procrustes analysis and a PCA (Dryden and Mardia, 1998; Lycett et al., 2006). The generalized Procrustes analysis serves here as a superimposition procedure, removing variability unrelated to shape, i.e., stemming from differences in location, orientation in space, and scale. When this procedure is followed, differences in landmark coordinates can be exclusively attributed to shape differences between the different tools (Dryden and Mardia, 1998). The PCA is the main analytical procedure in the shape analysis; it is used to reduce data dimensionality and detect the main axes of variability in the sample. Thus, it provides a number of components (i.e., variables or axes) equal to the number of items in the sample minus one, sorted in descending order according to the proportion of variability that they explain (Herzlinger and Goren-Inbar, 2019). Both GPA and PCA are developed automatically by the AGMT3-D software.

Each PC reflects a specific shape trend. Each analyzed tool receives a value for each PC, which is based on the values of its relevant coordinates in relation to the shape trend described by

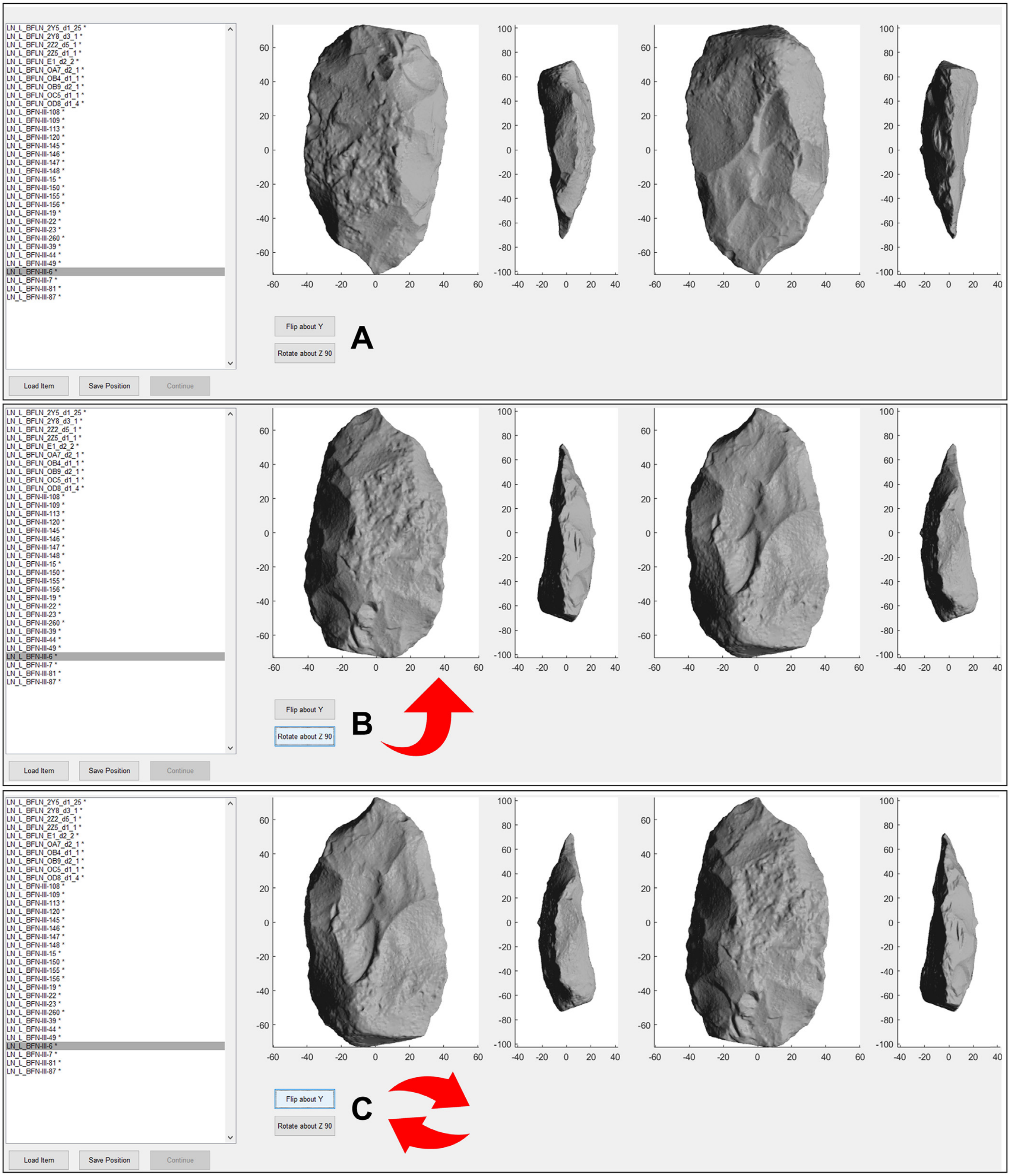

Figure 3. Screen shots during the positioning process in AGMT3-D v. 3.1: A) handaxe automatically oriented by the software. If this orientation is not correct, the software allows the user to manually change faces orientation ('flip about Y' button) (B), and/or C) change ends orientation ('rotate about Z' button) (C). The example shown is a handaxe from stratum a of la Noira (BFN_III_6).

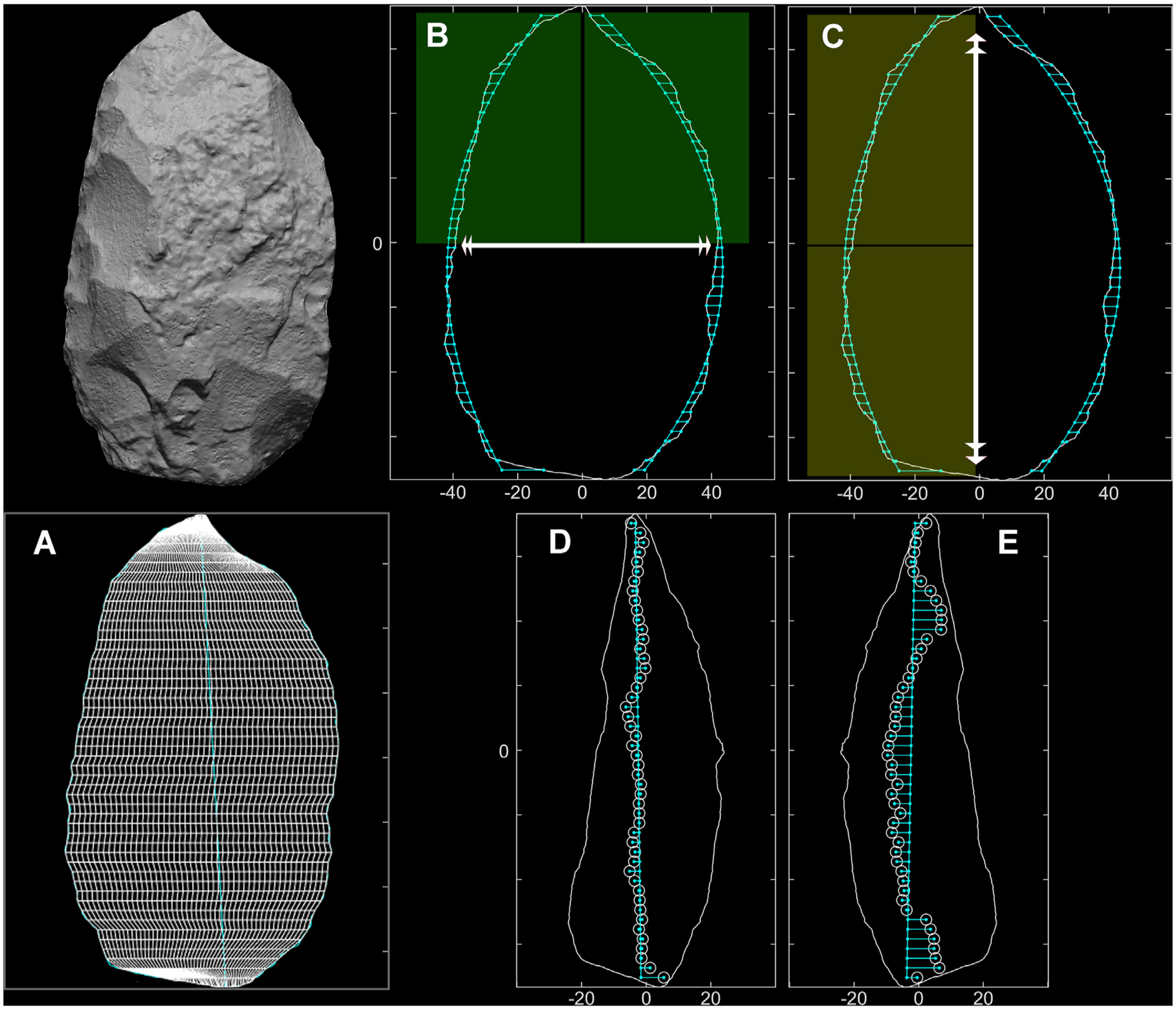

Figure 4. A) 5000 points defining outlines and tool surfaces. Edge curvature: visualization of deviation from perfect bilateral symmetry (B, in dark green) and perfect bifacial symmetry (C, olive green). D, E) Edge irregularity. Performed in AGMT3-D v. 3.1 The example is a handaxe from stratum a of la Noira (BFN_III_6). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

that particular PC. These multidimensional vectors allow us to determine the mean shape for each assemblage and use these means to calculate the intra- and inter-assemblage shape variability (Costa, 2010; Herzlinger and Goren-Inbar, 2019, 2020). Intra-assemblage shape variability is expressed here as the mean multidimensional Euclidean distance of all items in a given group from its group centroid. In addition, the results can be used to describe graphically and quantitatively the essence of shape differences in and between the assemblages. Differences in intra-assemblage shape variabilities and assemblage mean shapes are tested for statistical significance by applying the nonparametric Wilcoxon rank-sum tests to different data sets of interpoint distances.

In addition, multivariate analysis of variance (MANOVA) was used to evaluate whether the differences between multiple groups were statistically significant. The latest version of AGMT3-D v. 3.1 also offers quantitative approaches to the analysis of shape variation. First, we used the surface analysis (inches^2) and volume (inches^3) data to apply a quantitative approach to reduction intensity. The scar density index (SDI; Clarkson, 2013; Shipton and Clarkson, 2015a, 2015b) has been defined as the number of flake scars (greater than 10 mm in maximum dimension) divided by the surface area (in^2). As noted by García-Medrano et al. (2019), due to a loss of information during the knapping process, the correlation between SDI and volume information may establish a useful relationship between the number of scars and tool size. We thus applied a one-way analysis of variance to assess the relationship between SDI and volume at each site/sublevel.

The landmark data were also used to calculate the degree of deviation from perfect bilateral (Fig. 4B) and bifacial symmetries (Fig. 4C), as well as edge section regularity (Fig. 4D) of each item in the sample. The bilateral symmetry analysis was conducted by measuring the mean 3D Euclidean distance between a mirror reflection of the landmarks placed on one lateral half of each object and the corresponding landmarks on the other half. The same procedure was performed for bifacial symmetry, but on the two opposing faces. In a perfect bilaterally or bifacially symmetrical object, the value of these indices will be 0, with increasing values indicating less symmetry (Herzlinger and Goren-Inbar, 2020).

The resulting data from the methods as described earlier were used to address whether any diachronic technological change reflected external introduction, or more gradual internal development (RQ3).

Analysis of raw materials To address RQ4, we undertook a comparison of the different raw materials that were used at the different sites to assess whether raw material type determined the choices made in knapping and tool production. In addition to rock type, we include the proximity to source. We consider a 10 km limit to be a local procurement, whereas a radius greater than 10 km is considered a regional procurement (Binford, 1982; Fernandes et al., 2008). In addition, an approximate categorization of the size of original cobbles, nodules, or blocks was made where known as: small <10 cm; medium 10–20 cm; large >20 cm. A more reliable indication of the size of blanks used (cobbles, nodules, blocks, or flakes) was assessed from the tool length and width data (mean and range), which provided minimum estimates. The study of the quality of raw material is more subjective but was assessed through obvious flaws, such as frost-shatter, in the finished tools. The quality of the material for knapping was given as poor, medium, or good, varying from coarse-grained materials with a disorganized crystal structure, sometimes with internal fissures, to finer materials with well-organized internal crystals. Finally, there are several technological features of the tools that are largely independent of blank size, i.e., soft hammer use, tranchet finishing, S-twists on tool side profiles, and imposition of symmetry. These were all assessed in the technological and morphometric analyses and are discussed in the context of RQ4.

3. Results

3.1. Technological analysis

Using a PCA combining all the technological features (tool as one unit, tip of tools, midsection of tools, and butt of tools; see SOM Tables S1–S4), we evaluated the differences and similarities among sites in Western Europe between MIS 17 and MIS 8. More than 95% of the variability is explained by the first 10 PCs (SOM Table S5). However, the best characterization of this assemblage results from the combination of PC1 and PC2 (Fig. 5), which accounts for ~58% of the variation. Principal component 1 (42.34%) shows the variation from longer and more intense shaping (positive values) to shorter knapping sequences with extensive presence of cortex (negative values). Principal component 2 (15.47%) represents tools on cobbles but with a great variety of shaping strategies (positive values) vs. tools on flakes with more extensive cortex and clear short sequences, without final retouch (negative values). This PCA shows the existence of two main technological groups (Groups 1 and 2), plus Cagny-la-Garenne (Group 3) that graphically appear separate from the first two groups. The K–W analysis for PC1 and PC2 indicates that the median differences among these three groups are statistically significant ($p = 0.0066$), while M–W U tests (Table 3) reveal the median ranks of PC1 and PC2 to be significantly different in all three pairwise comparisons between groups. Group 1 is distinguished completely from Group 2 along PC1, while Group 3 is more similar to Group 2 than to Group 1 (Table 3). Group 1 consists of the assemblages from la Noira, Brandon Fields, Boxgrove, Elveden, Swanscombe–UMG, and St-Pierre-les-Elbeuf, all situated in central and Northern France and the UK. By contrast, Group 2, with the assemblages from Atapuerca and Menez-Dregan, lies in Western France and Northern Spain. Group 3 (Cagny-la-Garenne) is in Northern France.

Before characterizing each group, we first discuss la Noira, stratum a (LN.a). It is the oldest assemblage, dating to MIS 17/16, and appears in the center of the graph (Fig. 5). In 64% of cases, tools were made on millstone slabs, and in 22.58% of cases, they were made on flakes. They are characterized by the use of hard hammer, combined with soft hammer on specific parts of the tools, which

Table 3
Results of pairwise Mann–Whitney U tests for differences in mean principal components 1 and 2 between technological Groups 1, 2, and 3 (see also Fig. 4).

Group comparisons	Sites (n)	U	z	p-value
Groups 1/2	7/6	80	0.2051	0.0034
Groups 1/3	7/2	28	1.0596	0.1073
Groups 2/3	6/2	12	2.0479	0.6171

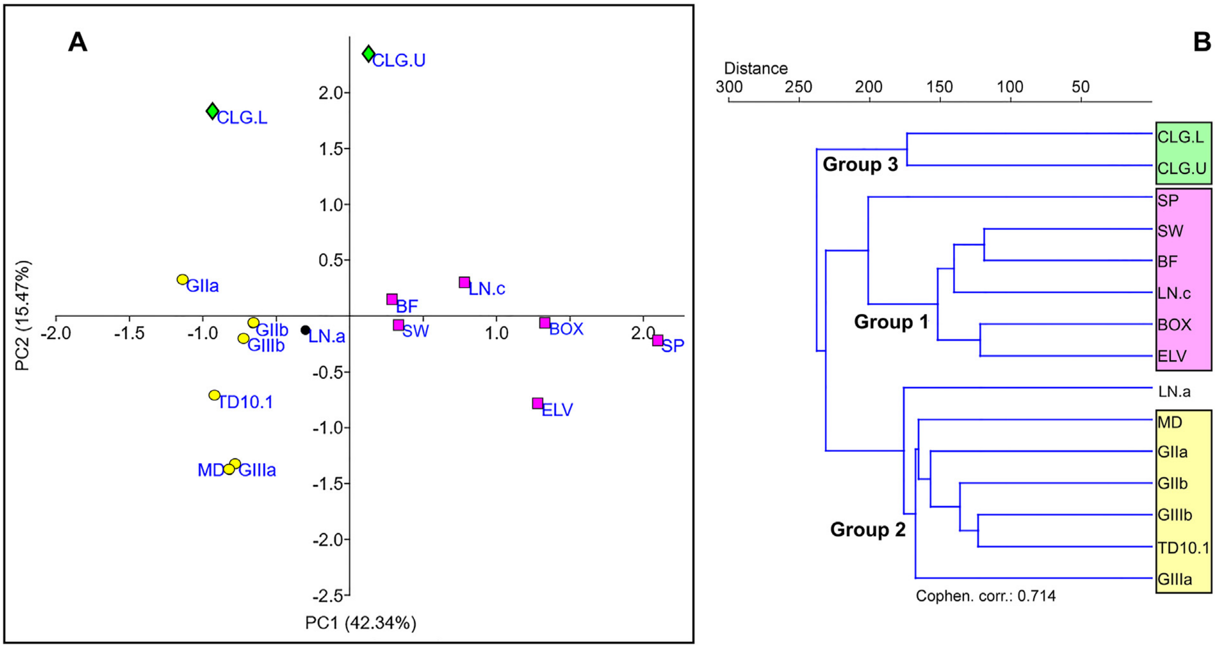

Figure 5. A) Principal component analysis combining all technological features analyzed in this study showing the distribution of all sites and B) and cluster analysis based on PC scores. According to the technological features of their large tools, sites appear organized into three main groups, Group 1 (in pink), Group 2 (in yellow), and Group 3 (in green). Abbreviations: PC, principal component; BF, Brandon Fields; BOX, Boxgrove; SW, Swanscombe-UMG; ELV, Elveden; LN.a, la Noira stratum a; LN.c, la Noira stratum c; MD, Menez-Dregan; SP, Saint-Pierre-lès-Elbeuf; CLG.L, Cagny-la-Garenne Lower Level (Ca); CLG.U, Cagny-la-Garenne Upper Levels (Cxb, Cxv); GIIa, GIIb, GIIIa, GIIIb = Galería, Atapuerca; TD10.1, Gran Dolina; Cophen. Corr*. = cophenetic correlation. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

created sinuous and non-symmetrical profiles (Fig. 6). The tips of tools were mainly shaped with only one removal series. On a small proportion, there were two removal series, sometimes combined with final retouch using soft hammer. The removals deeply affected the tool edges, creating very denticulated planforms. When only one series of removals occurred, this was noninvasive over the tool's surface, being close to the edge. When there were two or more removal series, they were much more invasive, affecting up to the midpart of a tool's surface. Finally, the butts retain 40–90% of the original cortex, and if there was any shaping, it consisted of just one noninvasive removal series produced by hard hammer percussion (SOM Table S4; Fig. 7). Thus, the Large Cutting Tools from la Noira stratum a are highly standardized, with a clear difference between tips and butts. The tips show more careful treatment, whereas the butts remain mainly cortical. The assemblage's position in the graph (Fig. 5) is noteworthy because it shows a technological distance from the later sites from Group 1, due to the increase in complexity which appears from MIS 15 to MIS 13.

Group 1 The sample from Brandon Fields dating to MIS 15 is exclusively on flint, with a notable increase in unknown blanks due to the intensity of knapping (12.9% in stratum a of la Noira, 48% at Brandon Fields; Table 4). The proportion of cobbles to flakes at Brandon Fields is balanced (24% and 28%, respectively; Table 4). There is an important technological difference from la Noira stratum a. First, a greater percentage of the perimeter is affected by shaping, and the non-cortical tools increase from 3% at la Noira to 34% at Brandon Fields, where the cortex is residual on the butts in 32% of cases (SOM Table S1). The shaping at Brandon Fields is developed mainly through two removal series with final retouch. In this case, the reduction sequence affects not only the tips but also the midsections and occasionally the butts of tools, so there is an increase in shaping intensity. Second, in contrast to la Noira stratum a, the second removal series is more invasive, affecting the central parts of the tools, rather than just the edges. Third, at Brandon Fields, there is more final retouch, which extends to the midsection and butts of the tools. Finally, there is a greater use of soft-hammer flaking (SOM Table S1).

The PCA and the cluster analysis together show that Brandon Fields at MIS 15 shares several technological features with the other British sites from MIS 13 to MIS 11 (Boxgrove, Swanscombe-UMG, and Elveden) as well as with some of the MIS 11 French sites (la Noira stratum c and St.-Pierre-lès-Elbeuf; Fig. 5). This group of sites is distributed along PC1, which explains 42.34% of the variability. Only flint was used at these sites, other than la Noira stratum c, with siliceous millstone slabs. The main technological difference that we have documented between MIS 17 and MIS 15 assemblages is the effect that the removal series had on the tools. Around MIS 17, the shaping was mainly aimed at defining the general shape of tools. But the increase in the invasiveness of several series of removals in MIS 15 aimed not only to define the shape but to reduce the thickness of tools. It seems to have been a cumulative process, from MIS 15 to MIS 13 and MIS 11 in this aspect (Fig. 6). From MIS 13, the shaping was characterized by longer operative chains, with at least two invasive removal series on the tools. The final retouch on tips was very intense and specific, and in most cases was the last worked part of the tool, either finishing with careful tranchet blows as at Boxgrove, or a combination of removals specific to the tip at the other sites (Fig. 7). Elveden, Swanscombe–UMG, and St.-Pierre-lès-Elbeuf in MIS11 best represent these techniques. Elveden and St.-Pierre are characterized by the combination of two removal series with final retouch across the whole piece, including butts, with particular attention paid to edges and thickness reduction. All three parts of the tools were treated in a similar way, exemplified by the 'twisted ovate' handaxes from Elveden (White, 1998a; Shipton and White, 2020). In the case of Swanscombe–UMG, tools retain more cortex and the butts only have one removal series, with less care on proximal parts.

La Noira stratum a presents the widest edge angles, with a progressive decrease in angles from MIS 17/16 to MIS 11 in Group 1 (Fig. 8A), which corresponds with a progressive decrease in tool volume (Fig. 8D), due to the increase in thinning (SOM Table S6). There is less difference between the distal and proximal parts of handaxes from Boxgrove and Elveden, both showing intense shaping on the butts (SOM Table S4).

Comparing the volume of tools with the SDI in Group 1, there is a decrease in volume and an increase in SDI from MIS 17 to MIS 11, but with exceptions (e.g., St.-Pierre). The relationship between volume and SDI (reflected by r^2) points to an increase through time related to the intensity of the knapping strategy, from MIS17 to MIS11, with the exception of Brandon Fields (Table 5). The use of flakes for shaping or the fragmentation of the initial blanks during the knapping process produced a significant loss of information and the strength of the relationship between volume and SDI decreased, e.g., Boxgrove (García-Medrano et al., 2019). In our samples, this pattern has been shown especially with Group 1, where knapping is mainly on cobbles or unknown blanks (Table 4).

Groups 2 and 3 The sites of Groups 2 and 3 are all in the Iberian Peninsula and France and date between MIS 12 and MIS 8–7, with Group 2 consisting of all the Atapuerca units (GIIa, GIIb, GIIIa, GIIIb) together with the basal levels from Menez-Dregan (MD, Levels 8 and 7), while Group 3 is composed of both the Lower and Upper Levels from Cagny-la-Garenne (CLG.L and CLG.U) (Fig. 5). The use of cobbles/nodules for shaping associates Cagny-la-Garenne (100% of tools from the Lower levels and 72% from the Upper levels) with the base levels of Galería (54% of tools; Table 4). In addition, these assemblages tend to show shorter sequences, with only one removal series. In the case of Galería (GIIa), the combination of two removal sequences was mainly concentrated on tips or midsections to create convergent edges and roughly reduce the thickness of pieces (Fig. 7). The butts and midsections are mainly cortical and the hominins predominantly used hard hammer, taking advantage of the morphological features of the cobbles (Fig. 9). In the case of Atapuerca, this technology evolved up the sequence, with the increasing predominance of flakes for making large tools, from GIIb sublevel, while the intensity of shaping decreased with marginal knapping. The shaping is characterized by only one removal sequence, with a few big blows having a deep effect on edges and very invasive across surfaces (SOM Tables S1–S4). These technical sequences imply that little attention was paid to the edges or thickness of tools, mainly to the tip thickness (T1, SOM Table S6).

The edge angles of bifaces of Group 2 contrast with most of those from Group 1, with steeper angles, similar to those documented in stratum a of la Noira (Fig. 8). The difference in angles between the distal and the butt parts of these tools is 10–15°, and the mean values are very similar in all levels. This corresponds with less care taken on edges and more basic shaping strategies in order to achieve a general tool shape. Metrically, this is reflected in less elongation and an absence of refined tools. Despite this, the tools from Galería GIIb and Menez-Dregan have large volumes (Fig. 8) because the blanks used are longer, wider, and thicker than the others. For Cagny-la-Garenne, the Lower levels show edge angles very similar to those in la Noira stratum a and the base levels of Galería (Atapuerca) (Fig. 8). However, there is an important fall in edge angles in the Upper Levels of Cagny-la-Garenne, with a mean reduction of 5–10° in the midupper tool sections, due to the application of several series of removals and final retouch on tips and midparts (Fig. 8B, C). The Atapuerca tools present similar volumes (except GIIb) to the Group 1 sites from MIS 15 to MIS 11, while the SDIs and scar counts are generally lower than Group 1. This means there is less intense flaking than Group 1. Thus, the volume

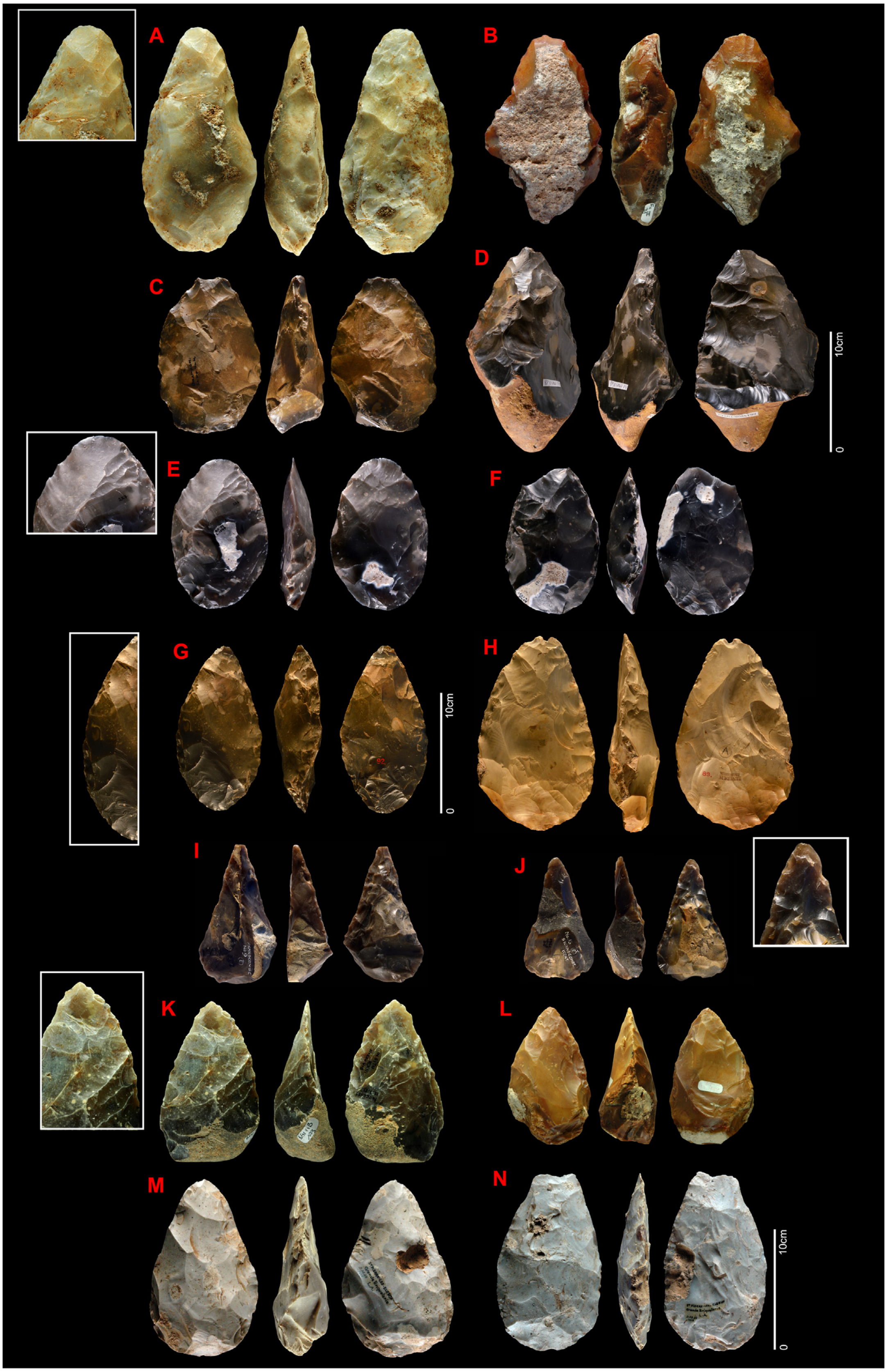

Figure 6. Group 1 Handaxes. A, B) la Noira stratum a (MIS 17–16); C, D) Brandon Fields (MIS 16–15); E, F) Boxgrove (MIS 13); G, H) Elveden (MIS 11c); I, J) Swanscombe-UMG (MIS 11c); K, L) la Noira stratum c (MIS 12); M, N) Saint-Pierre-lès-Elbeuf (MIS 11). They show specific tip-shaping techniques, tranchet removals, and care to edges.

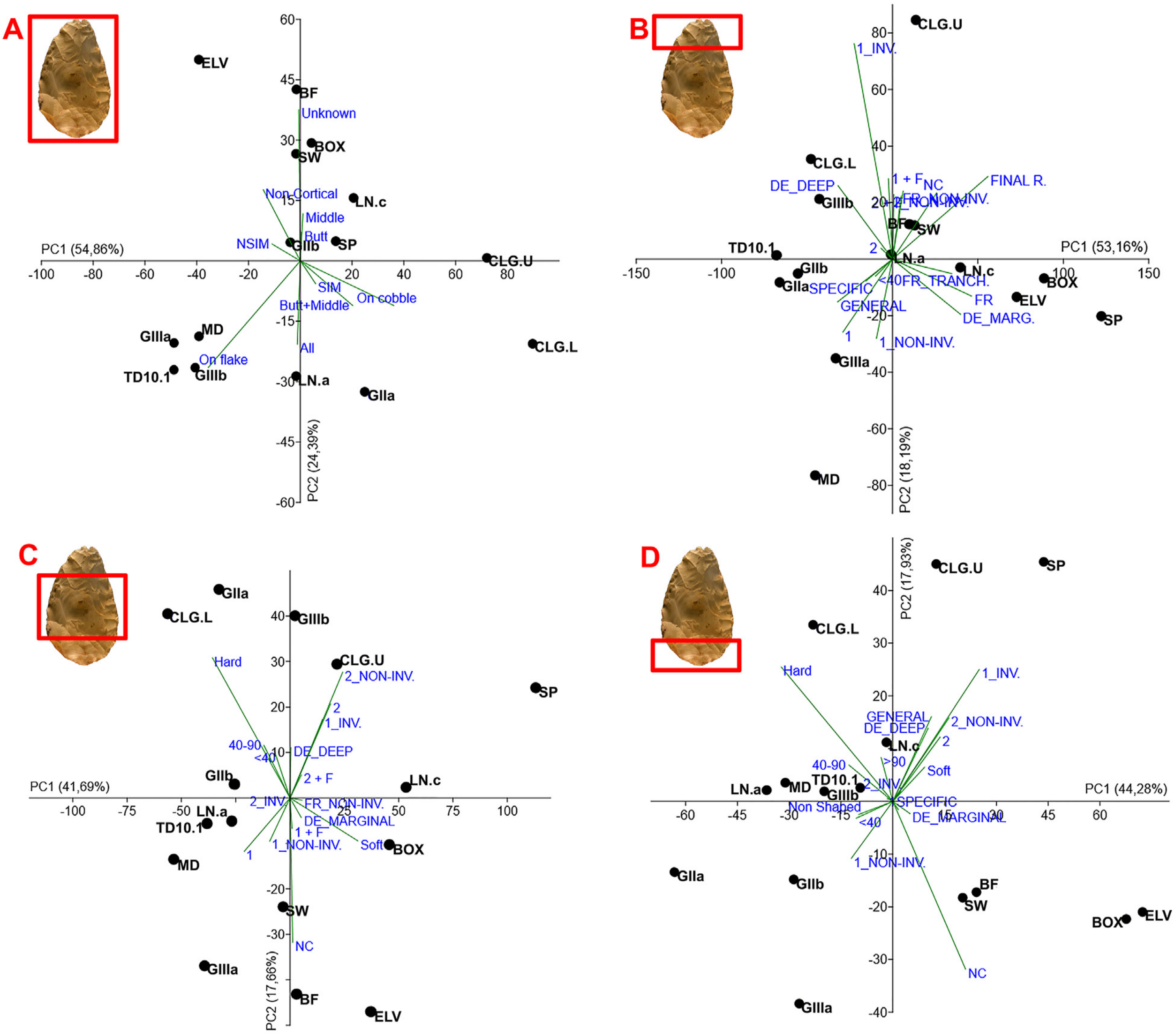

Figure 7. Principal components analysis (PCA; biplots) of the technological features that have a major effect on each group. The four graphs correspond to the technological variables included in Figure 3 but are divided into: A) tool as one unit; B) tip; C) midsection; and D) butt, according to SOM Tables 1–4. Abbreviations: PC, principal component; ELV, Elveden; BF, Brandon Fields; BOX, Boxgrove; SW, Swanscombe-UMG; LN.c, la Noira stratum c; GIIa, GIIb, GIIIa, GIIIb = Galería, Atapuerca; SP, Saint-Pierre-lès-Elbeuf; CLG.L, Cagny-la-Garenne Lower Level (Ca); CLG.U, Cagny-la-Garenne Upper Levels (Cxb, Cxv); MD, Menez-Dregan; TD10.1, Gran Dolina.

of tools of Atapuerca is less affected by the quantity of scars compared to Group 1. Here we have both the predominant use of flakes from GIIb and fewer, but bigger scars, to obtain a general shape (Table 5).

3.2. Geometric morphometric analysis

The GM analysis shows high and consistent intra-assemblage variability for Group 1 (Table 6) and Groups 2 and 3 (Table 7), obscuring the distinctiveness of each site and giving the false impression of homogeneity. To facilitate our interpretation, we have divided the analysis according to the main technological groups. Figure 10A shows the PCA and cluster analysis with all Group 1 sites, Figure 10B with sites included in Groups 2 and 3. In both cases, more than 70% of the variability is explained by the first 10 PCs. However, after a deep exploration of the shape trends expressed by the different PCs, the best characterization of these assemblages results from the combination of PC1 and PC2.

In Figure 10A, B, PC1 represents oval shapes (with the maximum width at midsections) to more pointed forms, with a shift of the maximum width to the midproximal part. By contrast, PC2 mainly explains the variation in tool thickness. All sites share the center of the graph: the teardrop shape is the general common morphology from around MIS 17 to 15, with wider, thicker tools at both la Noira stratum a and Brandon Fields. The MANOVA on the first 10 PCs of the Group 1 sites shows no significant differences. All these assemblages present a similar distribution of tools (Table 8), and the Wilcoxon rank-sum test on the interpoint distances between the means of these groups shows that differences between la Noira stratum a and Brandon Fields are not statistically significant (LN.a $n1 = 31$, BF $n2 = 49$, rank sum $= 6476$, $p = 0.3400$).

Despite technological continuity, the MIS 13 tools from Boxgrove show a significantly different shape from LN.a (LN.a $n1 = 31$, BOX $n2 = 45$, rank sum $= 4873$, $p < 0.0001$; Table 6). The intensity of shaping and thinning produces the most standardized sample, with nearly equal contributions from width, length, and thickness, and a clear tendency to rounder, thinner shapes (Table 6). By contrast, in France, la Noira stratum c (LN.a $n1 = 31$, LN.c $n2 = 43$, rank sum $= 4915$, $p < 0.0001$) and Saint-Pierre-lès-Elbeuf (LN.a $n1 = 31$, SP $n2 = 8$, rank sum $= 1313$, $p < 0.0001$) differ significantly

Table 4
Sample sizes and percentages of handaxes and cleavers according to the type of blank used for shaping.

Site/sublevel	Cobble/ nodule/slab		Flake		Unknown blanks		Total
	(n)	%	(n)	%	(n)	%	(n)
BF	12	24.00	14	28.00	24	48.00	**50**
BOX	14	28.57	16	32.65	19	38.78	**49**
SW	9	18.37	19	38.78	21	42.86	**49**
ELV	–	–	14	48.28	15	51.72	**29**
LN.a	20	64.52	7	22.58	4	12.90	**31**
LN.c	18	38.30	13	27.66	16	34.04	**47**
MD	1	5.00	15	75.00	4	20.00	**20**
SP	3	37.50	3	37.50	2	25.00	**8**
CLG.L	14	100.00	–	–	–	–	**14**
CLG.U	13	72.22	1	5.56	4	22.22	**18**
GIIa	7	53.85	6	46.15	–	–	**13**
GIIb	4	23.53	9	52.94	4	23.53	**17**
GIIIa	2	15.38	11	84.62	–	–	**13**
GIIIb	1	11.11	10	88.89	–	–	**11**
TD10.1	2	6.90	26	93.10	–	–	**28**
Total		**107**	**177**		**113**		**397**

Abbreviations: BF = Brandon Fields; BOX = Boxgrove; SW = Swanscombe-UMG; ELV = Elveden; LN.a = la Noira stratum a; LN.c. = la Noira stratum c; MD = Menez-Dregan; SP = Saint-Pierre-lés-Elbeuf; CLG.L = Cagny-la-Garenne Lower Level (Ca); CLG.U = Cagny-la-Garenne Upper Levels (Cxb, Cxv); GIIa, GIIb, GIIIa, GIIIb = Galería, Atapuerca; TD10.1 = Gran Dolina, Atapuerca.

from LN.a and tend clearly toward pointed tools, with maximum thickness on the midproximal sections of the pieces and a significant reduction in the distal width and thickness. In Britain, there were completely different forms in MIS 11 sites; from Boxgrove to Elveden (BOX $n1 = 45$, ELV $n2 = 30$, rank sum = 4720, $p < 0.0001$), there is a clear consolidation of the oval shapes, with the major variability concentrated in length and width and presenting more homogeneity in thickness. By contrast, Boxgrove and Swanscombe–UMG present very different shapes (BOX $n1 = 45$, SW $n2 = 51$, rank sum = 7042, $p < 0.0001$). Swanscombe–UMG has a clear tendency toward more pointed and thicker shapes, with maximum variability concentrated on tool width and thickness (Table 6).

Groups 1, 2, and 3 share the same space in the PCA plots due to high intra-site variability (Fig. 10A, B). Nevertheless, Groups 2 and 3 (Fig. 10B) show quantitative differences between each other with respect to Group 1. In both graphs (Fig. 10A, B), PC1 represents a transition from oval to pointed shapes, and PC2 from thicker (positive values) to more refined shapes (negative values). Nevertheless, Cagny-la-Garenne (CLG, lower and upper levels) is clearly disconnected from the other groups, mainly in the Lower levels, in terms of both technology and morphometry. Tools from Cagny-la-Garenne have their maximum variation concentrated on width and thickness (Table 7). The PCA shows how the CLG assemblage

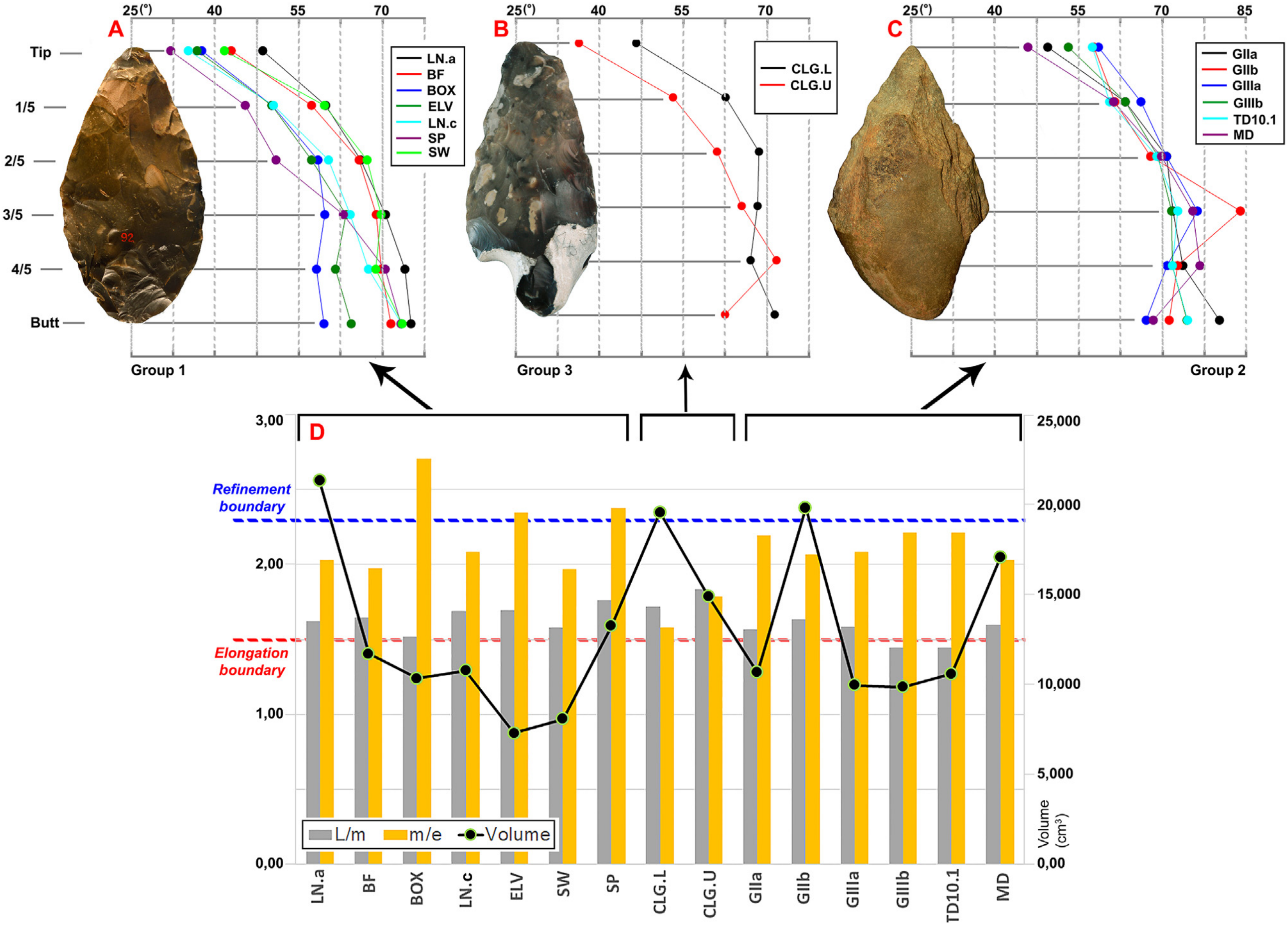

Figure 8. A–C) Angles along tool edges by sites. The dots reflect the mean values in each case. D) Histogram with elongation (gray) and refinement data (yellow) by sites, combined with volume information (line and dots). Group 1 shows a progressive decrease in volume and angle pattern, as well as refinement. Groups 2 and 3 present a more random distribution of sites with a clear tendency toward wider angles. Abbreviations: LN.a, la Noira stratum a; BF, Brandon Fields; BOX, Boxgrove; ELV, Elveden; LN.c, la Noira stratum c; SP, Saint-Pierre-lès-Elbeuf; SW, Swanscombe-UMG; CLG.L, Cagny-la-Garenne Lower Level (Ca); CLG.U, Cagny-la-Garenne Upper Levels (Cxb, Cxv); GIIa, GIIb, GIIIa, GIIIb = Galería, Atapuerca; TD10.1 = Gran Dolina, Atapuerca; MD, Menez-Dregan. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 5
Relationships between volume and scar density index values based on analysis of variance for each site/sublevel. Scar numbers (means) are also included to evaluate their meaning as an independent technological feature. Note that in some cases, numbers of pieces (n) differ from the total number included in the study because for the GM analysis we excluded the fragmented tools.

Site/sublevel	MIS	n	Scar number (mean)	Volume (mean)	SDI (mean)	F	p-value	r^2
LN.a	MIS 17/16	31	20	20647.74	0.065	11.06	<0.01	0.276
BF	MIS 15	47	19.70	11799.11	0.097	40.05	<0.01	0.470
BOX	MIS 13	45	20.20	10413.05	0.082	16.31	<0.01	0.279
LN.c	MIS 12	43	21.11	10761.83	0.101	24.08	<0.01	0.370
ELV	MIS 11	27	22.62	7407.22	0.135	12.20	<0.01	0.328
SW	MIS 11	47	16.38	8218.66	0.104	41.14	<0.01	0.477
SP	MIS 11	8	24.12	13250.34	0.096	16.74	<0.01	0.736
CLG.L	MIS 12	13	16.15	20370.87	0.059	4.86	0.05	0.306
CLG.U	MIS 11	17	18.94	14890.33	0.082	9.07	<0.01	0.376
GIIa	MIS 12/11	13	15.07	10673.66	0.078	2.18	0.16	0.160
GIIb	MIS 8/7	11	16.27	19827.91	0.049	0.06	0.80	0.007
GIIIa	MIS 8/7	4	14.5	10621.81	0.071	0.90	0.44	0.312
GIIIb	MIS 8/7	7	15.42	10323.61	0.073	0.56	0.49	0.100
TD10.1	MIS 10/8	12	8.41	9500.88	0.051	1.02	0.33	0.092
MD	MIS 11	20	10.3	17054.87	0.039	12.08	<0.01	0.415

Abbreviations: LN.a = la Noira stratum a; BF = Brandon Fields; BOX = Boxgrove; LN.c. = la Noira stratum c; ELV = Elveden; SW = Swanscombe-UMG; SP = Saint-Pierre-lés-Elbeuf; CLG.L = Cagny-la-Garenne Lower Level (Ca); CLG.U = Cagny-la-Garenne Upper Levels (Cxb, Cxv); GIIa, GIIb, GIIIa, GIIIb = Galería, Atapuerca; TD10.1 = Gran Dolina, Atapuerca; MD = Menez-Dregan; SDI, scar density index.

differs from the others (Fig. 10B), with a tendency toward pointed and thicker pieces, something which remains constant through the CLG sequence (CLG.L $n1 = 14$, CLG.U $n2 = 17$, rank sum = 920, $p = 0.4300$). Group 2 (Atapuerca assemblages and Menez-Dregan) appears associated with a high frequency of oval-shaped tools, with their maximum variability concentrated on length and thickness (Table 7). These tools have convergent edges with a wider distal end.

One of the other characteristics of Group 2 is the presence of classic cleavers and cleaver-like tools (Fig. 12). Despite the presence of cleavers at other sites such as la Noira (Moncel et al., 2021), the proportion of these tools in comparison to strict handaxes—teardrop-shaped bifacial handaxes—is much higher in Group 2 than in Group 1, reaching 20% in Menez-Dregan and GIIa subunit (Galería) to 47% in GIIb (Table 1). A PCA on tools from Group 2 suggests a fairly subtle difference between handaxes and cleavers (Fig. 11A). The interpoint distance between the group means is statistically significant (handaxes $n1 = 93$, cleavers $n2 = 17$, rank sum = 10005, $p < 0.0001$). Despite the different sample sizes, the handaxes show 10% more variability than cleavers, which is a much more standardized group (Table 9). Figure 11B shows how the maximum variation of handaxes is localized on lateral edges, but the cleavers are thicker tools, and their shapes depend more on the proximal parts of tools and transverse distal ends. Nevertheless, despite differences in shape between both tool types, the K—W analysis for PC1 and PC2 indicates that the median differences between these groups are not statistically significant ($p = 0.6983$). Thus, the cleavers from Atapuerca and Menez-Dregan do not produce a change in the morphometric distribution of the Group 2 tools.

There is an average 20% increase in bilateral symmetry comparing the oldest site of la Noira stratum a with the other sites from Group 1 (SOM Table S7), reaching 47% with Boxgrove. Wilcoxon rank-sum tests confirm that this difference with Boxgrove is statistically significant (LN.a $n1 = 31$, Boxgrove $n2 = 45$, rank sum = 1860, $p < 0.0001$). Cagny-la-Garenne and Menez-Dregan present even less bilateral symmetry than la Noira, while the Atapuerca levels show a high variability. Bifacial symmetry shows a similar pattern, being the most symmetrical (i.e., the lowest deviation from symmetry) at Boxgrove and Elveden, sites which also have more intense shaping and thinning. Again, la Noira stratum a and Cagny-la-Garenne have between 10 and 20% less symmetry. Regarding the planform irregularity, both edges differ in regularity (SOM Table S7). Nevertheless, we can point out that tools from Group 1 present the most planform homogeneity, together with most symmetrical profiles. On the contrary, sites from Groups 2 and 3 have less symmetry and less homogeneity with this aspect. Thus, we can confirm that there is a clear relationship between long shaping sequences, combining several removal series, and final retouch with major edge regularity.

To summarize the GM results, most of the sites share the same morphological traits. The same teardrop shape varies in two main ways: (1) oval vs. pointed shapes resulting from position of maximum width; and (2) variation in tool thickness. Despite clear technological connections within Group 1, there is distance between the sites. The mean shapes from la Noira stratum a and Brandon Fields indicate a connection, with a clear tendency to oval forms. From MIS 13 to MIS 11, there is a technological link in Group 1, but the morphometry indicates different tendencies. Boxgrove (MIS 13) handaxes are the most standardized with more intense shaping and thinning and a tendency to rounder, thinner shapes. For MIS 11, in Britain, there are two expressions with Elveden having refined, ovate shapes and Swanscombe—UMG more pointed, thicker forms, while in France, la Noira stratum c and Saint-Pierre-lès-Elbeuf show a tendency toward pointed tools, with thicker mid-proximal sections and a reduction in distal width and thickness.

Groups 2 and 3 show similar distances from Group 1. Atapuerca and Menez-Dregan (Group 2) present more globular shapes. At Galería GIIa, the extensive use of flakes as blanks and progressively less shaping created wider tools, a feature shared with Menez-Dregan. Group 3 (Cagny-la-Garenne) stands apart, having pointed, thick tools. The morphology of Group 2 is strongly related to the form of the original blanks, with less intense knapping, consistent with the MANOVA results on the first 10 PC scores according to raw material (Table 10). Table 11 shows the strong similarity between sandstone (and other metamorphic rocks) with quartzite (and quartz), as well as millstone slabs, whereas flint shows a clear distance from other materials.

4. Discussion

4.1. *Acheulean variability in Western Europe*

Our study suggests the existence of three different technological groups among the selected Middle Pleistocene Western European sites. Group 1 with the assemblages from la Noira, St.-Pierre-les-Elbeuf, Brandon Fields, Boxgrove, Elveden, and Swanscombe—UMG

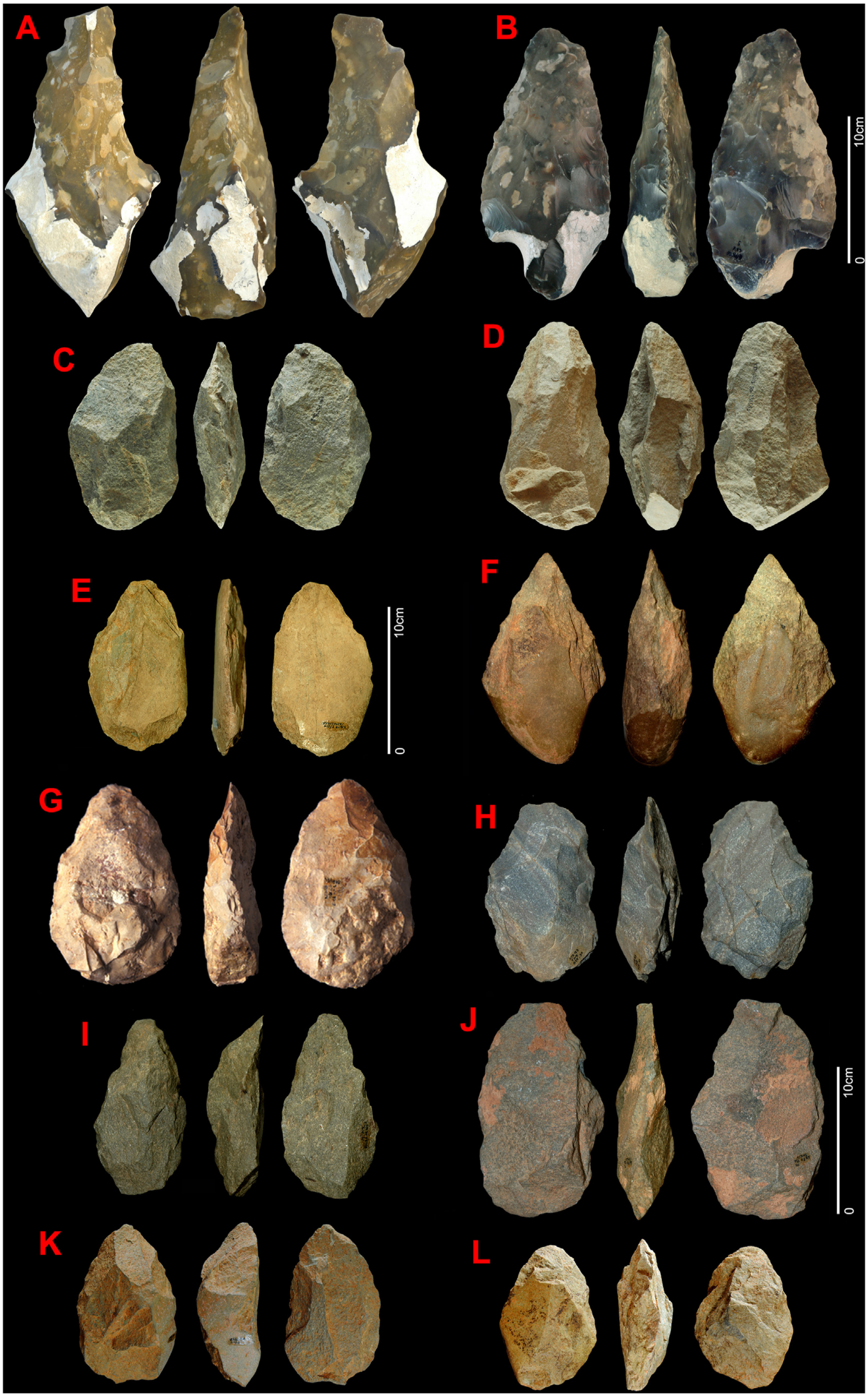

Figure 9. Handaxes from Group 2 and Group 3 sites. A, B) Cagny-la-Garenne I; C, D) Menez-Dregan; E, F) Galería-GIIa; G, H) GIIb; I) GIIIa; J) GIIIb; K, L) Gran Dolina-TD10.1. Compared to Group 1, handaxes from Groups 2 and 3 have shorter shaping sequences on a larger variety of raw materials, with no special treatment on tips, and less care to edges.

Table 6
Intra-assemblage shape variability analysis (measured as the mean multidimensional Euclidean distance of all artifacts from its centroid) and distribution of relative shape variability across dimensions of the handaxes from Group 1 sites (Fig. 9A). Note that in some cases, numbers of pieces (*n*) differ from the total number included in the study because for the GM analysis we have excluded the fragmented tools.

Site/sublevel	(*n*)	Shape variability	Variability (%) caused by:		
			x (width)	y (length)	z (thickness)
LN.a	31	7.92	50.00	2.67	47.33
BF	49	7.79	48.51	3.05	48.44
BOX	45	5.03	48.34	3.06	48.60
LN.c	43	7.78	49.49	3.65	48.86
ELV	30	7.73	56.73	5.10	38.18
SW	51	8.98	50.05	2.58	47.36
SP	8	7.32	41.00	1.37	57.63

Abbreviations: LN.a = la Noira stratum a; BF = Brandon Fields; BOX = Boxgrove; LN.c = la Noira stratum c; ELV = Elveden; SW = Swanscombe-UMG; SP = Saint-Pierre-lés-Elbeuf.

Table 7
Intra-assemblage shape variability analysis (measured as the mean multidimensional Euclidean distances of all artifacts from their centroid) and distribution of relative shape variability across dimensions of the handaxes from Groups 2 and 3 (Fig. 9B). Note that in some cases, numbers of pieces (*n*) differ from the total number included in the study because for the GM analysis we have excluded the fragmented tools.

Site/sublevel	(*n*)	Shape variability	Variability (%) caused by:		
			x (width)	y (length)	z (thickness)
CLG.L	14	10.75	53.16	1.68	45.16
CLG.U	17	8.39	47.53	1.86	50.60
MD	20	8.90	43.29	2.73	53.97
GIIa	13	8.10	49.06	3.40	47.54
GIIb	11	7.96	38.03	2.24	59.73
GIIIa	8	8.20	49.35	3.20	47.45
GIIIb	8	7.78	33.62	3.22	63.16
TD10.1	19	9.01	42.11	2.63	55.26

Abbreviations: CLG.L. = Cagny-la-Garenne Lower Level; CLG.U. = Cagny-la-Garenne Upper Levels; MD = Menez-Dregan; GIIa, GIIb, GIIIa, GIIIb = Galería, Atapuerca; TD10.1 = Gran Dolina, Atapuerca.

are situated in central and Northern France, and the UK, whereas Group 2 with the assemblages from Atapuerca and Menez-Dregan lie in Western France and Northern Spain, land connected throughout this period (Hijma et al., 2012). This clear geographical patterning addresses RQ1. Group 3 is more difficult to interpret. Cagny-la-Garenne lies beneath an eroding Chalk bluff, and with readily available fresh flint has been interpreted as a workshop, which influenced the technology and form of the handaxes (Lamotte, 1999; Lamotte and Tuffreau, 2001a, 2001b; Tuffreau and Lamotte, 2010). As raw material has a strong influence, the Cagny assemblages contribute little to question of geographical regions or chronological trends. In Group 1, we see a clear technological connection from the MIS 17/16 to MIS 11 assemblages. As the oldest Acheulean assemblage, the relatively standardized handaxes of la Noira stratum a suggest the appearance of an already established technology in Europe (Iovita et al., 2017; Moncel et al., 2020a, 2021; García-Medrano et al., 2022a). These handaxes were made by short shaping sequences, with one series of removals, mainly concentrated on mid-distal sections and the tool edges, which retain a large proportion of the original blank. This standardized type of shaping was sometimes combined with clear attention to the tips, with a specific combination of hard and soft hammer percussion, illustrating the control of shaping techniques at this time. What was occasional practice in la Noira stratum a technology became widely used at Brandon Fields (Britain) in MIS 15, with increased perimeter shaping, a reduction in cortex through additional removal series, and final retouch on the midsections of the tools. From MIS 13 to 11, shaping became more intense, as typified initially by Boxgrove and then by the MIS 11 sites. The aim was to create long, convergent regular edges, reducing tool thickness, and increasing bilateral and bifacial symmetry, which was all achieved through extensive soft hammer use (Caruana, 2020). There is thus a clear chronological patterning for the Group 1 sites (RQ2). Furthermore, in answer to RQ3, the patterning appears to be incremental, suggesting that there was internal development in technology within the region, rather than external innovation. The underpinning technical developments enabled through soft hammer use, the increased use of specific techniques at some sites. In particular, 'tranchet' removal from handaxe tips was used in MIS 13 at Boxgrove, where refitting suggests that it was for tip resharpening (Roberts and Parfitt, 1999). The technique created sharp distal ends, free of retouch, without substantially modifying tool morphometry, and has been suggested as a specific cultural trait (García-Medrano et al., 2019). Twisted ovates are mainly limited to sites in MIS 11 and for which there appears to be no functional advantage (White et al., 2019). As with 'tranchet' removals, it seems to have been a short-term, localized feature, as an expression of local cultural tradition. These regional and short-term variations have been interpreted as the identification of localized traditions of manufacture that represent small cultural groups on an ethnographic scale (Wenban-Smith, 2004; Bridgland and White, 2014; Ashton, 2015; White, 1998a, 1998b; White et al., 2019; Davis and Ashton, 2019; Ashton and Davis, 2021; Moncel et al., 2021b; García-Medrano et al., 2022a, b). By contrast, Groups 2 and 3 show higher variability and less standardization. These assemblages retain a basic Acheulean technology with the use of local cobbles (Galería-GIIa) or nodules (Cagny-la-Garenne) that kept some features of the original blank through cortex retention. Whereas Group 1 developed more intense knapping, Group 2 evolved in a contrasting way, whereby cobbles were substituted with flakes with a reduction in shaping intensity and widespread use of hard hammer percussion with only one removal series. The relation between number of removals and volume is weaker, showing less dependence between the final morphometry and the organization of shaping, while the plan and profile symmetries are less defined. The high proportion of cleavers fits well with this type of technology. These tools required less shaping intensity, which is mainly concentrated on lateral edges, keeping the distal edge free of retouch. There is a large variety of these tool types, particularly in the Atapuerca sites, where there are classical cleavers and also cleaver-like tools, shaped on cobbles (Fig. 12D) or with slightly retouched distal edges (Fig. 12F, J; García-Medrano et al., 2015). At Atapuerca, cleavers decreased through the sequence, and in subunit TD10.1, decreased in size, almost becoming small tools on flakes (de Lombera-Hermida et al., 2020).

For Group 2 sites, there also appear to be traditions of manufacture that can be demonstrated to be long-term (RQ2). Both Menez-Dregan and Atapuerca show the maintenance of distinctive approaches to technology from MIS 12 through to MIS 8, suggesting little innovation from outside the region. The gradual shift from cobble to flake-blank use at Galería supports the interpretation of internal developments, rather than external innovation, in answer to RQ3, suggesting the persistent return of closely related populations to the site. The significant presence of cleavers on flakes in the Group 2 assemblages, particularly at Atapuerca, requires further consideration in relation to RQ3. These types of cleavers have a significant presence in Acheulean assemblages across North Africa, the Levant, and East Africa, usually referred to as the Large Flake Acheulean (LFA; Goren-Inbar and Saragusti, 1996; Sharon, 2008, 2009; Sharon et al., 2011). The term derives from the modified flake component (>10 cm), which together with handaxes and chopping

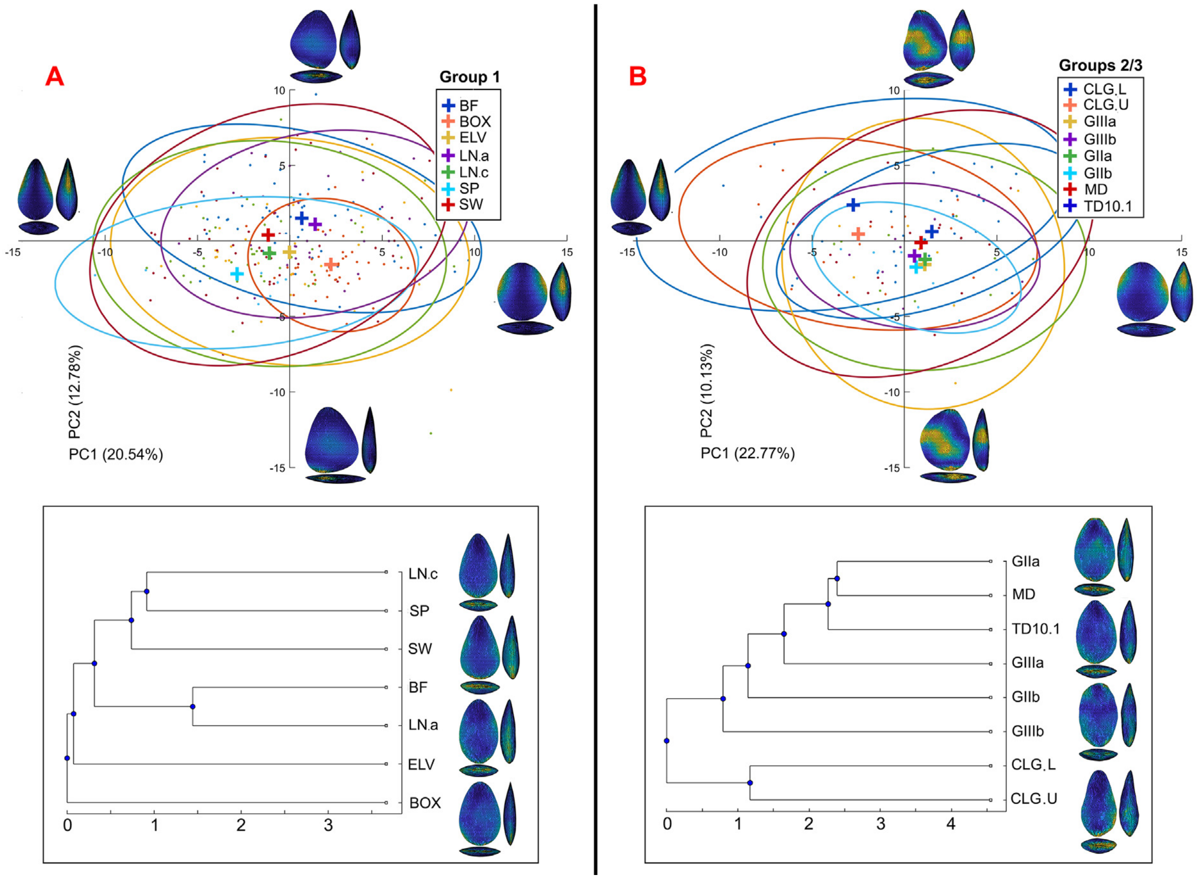

Figure 10. Principal component analyses on the 3D tool models, indicating the score of each assemblage's mean shape (+). Illustrations show hypothetical objects situated at the extremities of each PC, reflecting the shape trend each represents. Ellipses correspond to 95% confidence interval. Resulting cluster analysis with the mean shapes of some sites. A) Group 1; B) Groups 2 and 3. Abbreviations: PC, principal component; BF, Brandon Fields; BOX, Boxgrove; ELV, Elveden; LN.a, la Noira stratum a; LN.c, la Noira stratum c; SP, Saint-Pierre-lès-Elbeuf; SW, Swanscombe-UMG; CLG.L, Cagny-la-Garenne Lower Level (Ca); CLG.U, Cagny-la-Garenne Upper Levels (Cxb, Cxv); MD, Menez-Dregan; GIIa, GIIb, GIIIa, GIIIb = Galería, Atapuerca; TD10.1 = Gran Dolina, Atapuerca.

Table 8
Results of multivariate analysis of variance between the different sites/levels of Group 1 according to the analysis on the first 10 principal component scores (73.18% of variance). See also Figure 9A.

Sites/levels	BF	BOX	ELV	LN.a	LN.c	SW	SP
BF	–	<0.01	<0.01	0.047	<0.01	<0.01	0.009
BOX	<0.01	–	<0.01	<0.01	<0.01	<0.01	0.011
ELV	<0.01	<0.01	–	<0.01	<0.01	<0.01	0.042
LN.a	0.047	<0.01	<0.01	–	<0.01	<0.01	0.029
LN.c	<0.01	<0.01	<0.01	<0.01	–	<0.01	0.900
SW	<0.01	<0.01	<0.01	<0.01	<0.01	–	0.054
SP	<0.01	0.011	0.042	0.029	0.900	0.054	–

Abbreviations: BF = Brandon Fields; BOX = Boxgrove; ELV = Elveden; LN.a = la Noira stratum a; LN.c = la Noira stratum c; SW = Swanscombe-UMG; SP = Saint-Pierre-lés-Elbeuf.

tools come under the umbrella term of Large Cutting Tools. The tools of the LFA were characterized by short shaping sequences, mainly to regularize the volume and remove percussive bulbs, with cleavers having a significant presence. The presence of cleavers in the Iberian Peninsula has been used to propose a cultural connection with North Africa through the Strait of Gibraltar (Santonja and Villa, 2006). The Group 2 assemblages certainly fit well with the LFA definition and support a connection along the Atlantic coast with similar oceanic climates, avoiding the barrier of the Pyrenees Mountains (Cohen et al., 2012; Sharon and Barsky, 2016).

Although a geographical pattern has been identified between Groups 1 and 2, it could be argued that this is due to differences in raw materials between the regions (RQ4): did raw material type, quality, or availability limit the choices made by the knappers? Other than la Noira, at all the other Group 1 sites, handaxes and cleavers were made on local Cretaceous flint, but of varying quality from large nodules of fresh flint at Boxgrove to small-medium river cobbles at Swanscombe–UMG (Table 12). The quality of Cretaceous flint is generally good, but also quite brittle and subject to breakage along internal flaws or frost shatter (e.g., Ashton et al., 2005; García-Medrano et al., 2019). At la Noira, the local millstone, mainly good quality slabs, was used in both assemblages. Although frost-shattering affected some slabs, this material was generally avoided. For stratum c, Jurassic chert and Cretaceous flint as flakes and nodules were imported, the latter coming from between 30 and 100 km. The different types of raw material did not affect handaxe and cleaver forms, although those on flint were on average smaller (Moncel et al., 2021). The Group 1 sites all used a mix of flake blanks and other naturally occurring cobbles, nodules, or slabs for tool manufacture, but importantly the raw material was of varying quality. There was a wider variety of raw materials used at the Group 2 sites. For Menez-Dregan, the handaxes and cleavers were virtually all made on large flakes from local beach cobbles of sandstone, microgranite, quartzite, and quartz, with quality sufficiently good to produce large flakes for modification. At Atapuerca, the tools were made from local, medium-large, coarse-grained river cobbles of quartzite and other metamorphic rocks, occasionally of quartz, together with small Cretaceous chert cobbles, and large

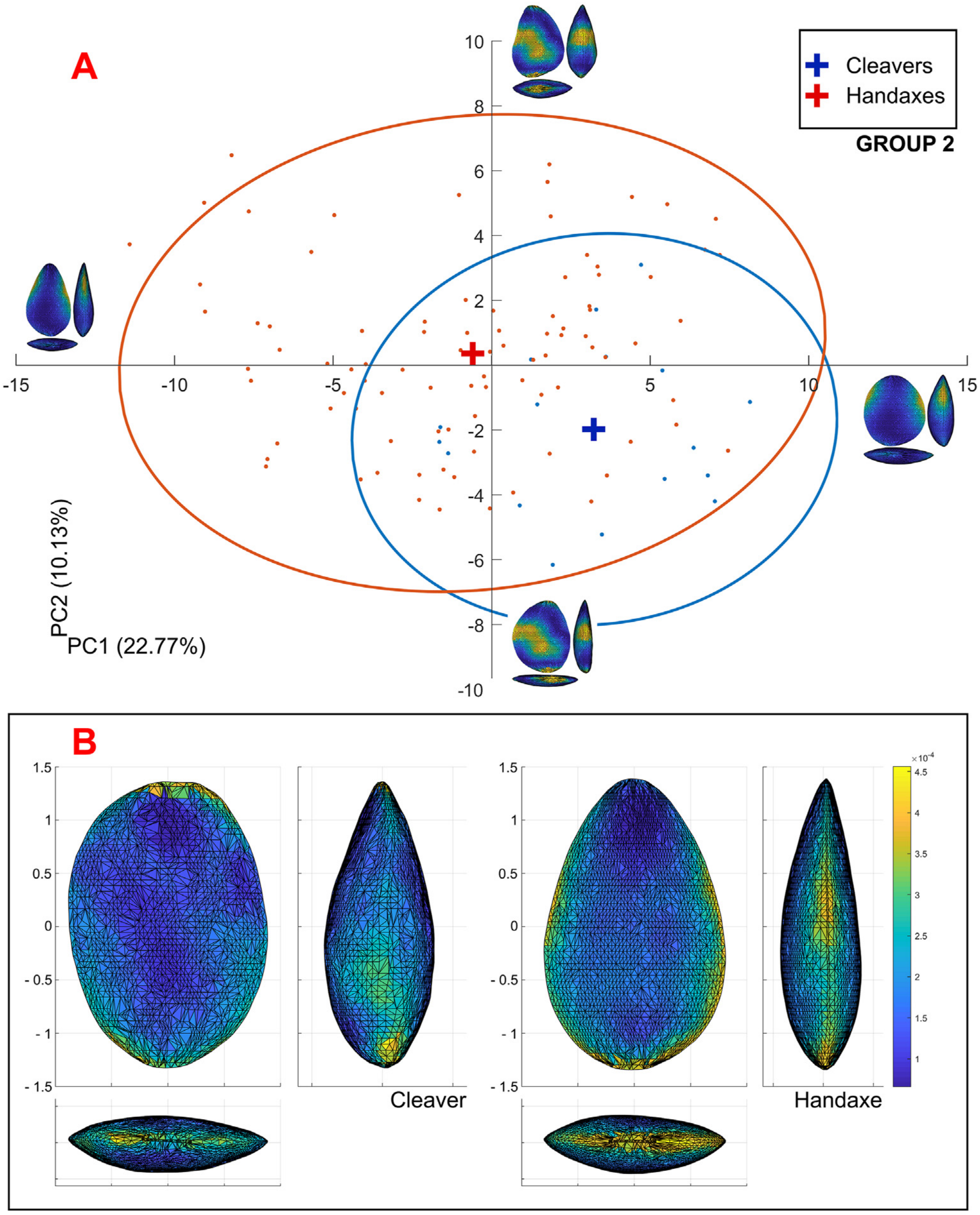

Figure 11. A) Principal component analysis on the Group 2 tools, considering cleavers and handaxes, indicating the score of each assemblage's mean shape (+). Illustrations show hypothetical objects situated at the extremities of each principal component, reflecting the shape trend it represents. Ellipses correspond to 95% confidence interval. B) Group mean shapes. Color code shows the range of variation in tool shape (yellow = maximum; blue = minimum). Abbreviation: PC, principal component. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Neogene chert blocks. They were all of medium to good quality. Overall, the various raw materials from the different sites appear to have imposed few limitations on knapping choices. This is supported by the size of the finished products (Table 12); there are few differences in the range of lengths and widths between the different sites, or between the groups. In summary, cleavers could be made in preference to handaxes or vice versa, while both flake blanks and cobbles were variously selected across the sites, but with a clear preference for the former at Menez-Dregan and the upper levels at Galería. Specific techniques could have been used, if chosen, such as soft-hammer flaking, tranchet-finishing, or twisted profiles. Equally, symmetry could have been imposed if required. Therefore, for Group 1, there appears to have been a clear selection on soft-hammer working, increased overall working, greater attention to edge form, imposition of symmetry, and occasionally an introduction of idiosyncratic techniques such as tranchet finishes and twisted profiles, compared to Group 2. Thus, in answer to RQ4, if differences in raw materials are not responsible for these group differences, then the most obvious conclusion is that there are different traditions of manufacture in the two regions over significant time scales. There always remains the possibility of convergent evolution, but this seems unlikely given the geographical and chronological patterns in the data (Shipton, 2020; Key, 2023).

4.2. Regional distinctions and long-term change: Implications for the Acheulean in Europe

Our analysis suggests that patterns of large tool shaping from around MIS 17 to MIS 11 in central and Northern France and Britain

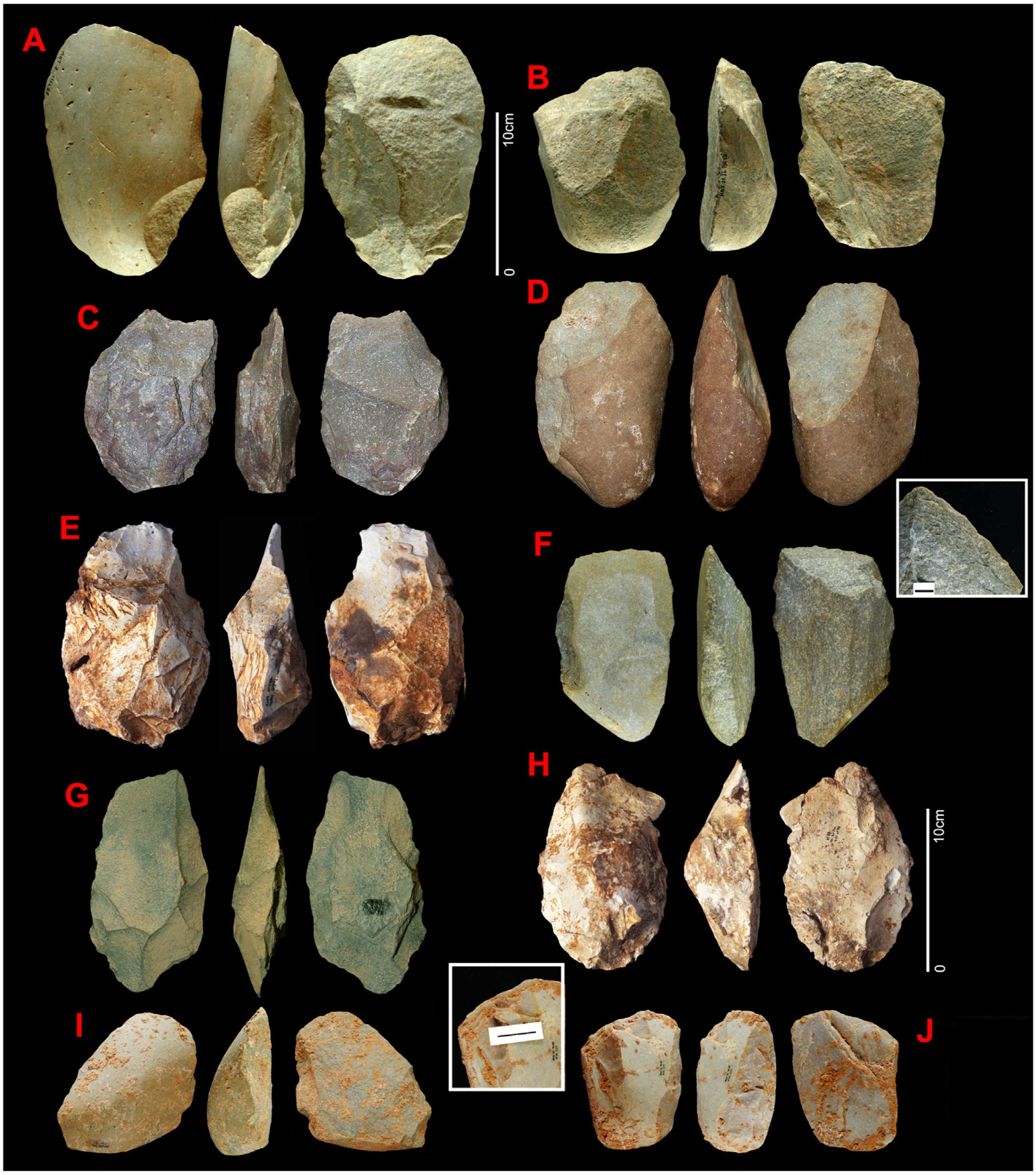

Figure 12. Cleavers from Group 2 sites. A, B) Menez-Dregan; C, D) Galería-GIIa; E, F) GIIb; G, H) GIIIa; I, J) Gran Dolina-TD10.1. This figure shows the high technological and morphometrical heterogeneity of cleavers and cleaver-like tools, with details on some retouched transverse distal ends.

were based on the accumulation of knowledge that developed in this region. Although there was significant cooling and probable depopulation in Northern Europe between the MIS 17/16 site of la Noira stratum a and the MIS 15 site of Brandon Fields, there is evidence of continuity and development in technology, implying that

Table 9
Intra-assemblage shape variability analysis (measured as the mean multidimensional Euclidean distance of all artifacts from their centroid) and distribution of relative shape variability of Figure 10A.

Tools	(*n*)	Shape variability	Variability (%) caused by:		
			x (width)	y (length)	z (thickness)
Cleavers	17	8.30	46.47	2.22	51.01
Handaxes	93	9.16	45.71	2.35	51.94

Table 10
Results of multivariate analysis of variance between the different sites/levels of Groups 2/3 according to the analysis on first 10 PC scores (71.06% of variance). See also Figure 9B.

Site/sublevels	CLG.L	CLG.U	MD	GIIIa	GIIIb	GIIa	GIIb	TD10.1
CLG.L	–	0.491	<0.01	0.193	0.063	0.034	0.025	0.013
CLG.U	0.491	–	0.216	0.503	0.170	0.255	0.076	0.139
MD	<0.01	0.216	–	0.890	0.396	0.998	0.518	0.954
GIIIa	0.193	0.503	0.890	–	0.817	0.980	0.910	0.858
GIIIb	0.063	0.170	0.396	0.817	–	0.624	0.395	0.754
GIIa	0.034	0.255	0.998	0.980	0.624	–	0.873	0.880
GIIb	0.025	0.076	0.518	0.910	0.395	0.873	–	0.236
TD10.1	0.013	0.139	0.954	0.858	0.754	0.880	0.236	–

Abbreviations: CLG.L. = Cagny-la-Garenne Lower Level; CLG.U. = Cagny-la-Garenne Upper Levels; MD = Menez-Dregan; GIIIa, GIIIb, GIIa, GIIb = Galería, Atapuerca; TD10.1 = Gran Dolina, Atapuerca.

Table 11
Multivariate analysis of variance (p uncorrected values) between the raw materials according to the geometric morphometric analysis on the first 10 principal component scores (71.14% of variance) of the total sites included.

Raw materials	Sandstone/metamorphic rocks	Chert/flint	Quartzite/quartz	Millstone
Sandstone/metamorphic rocks	–	0.0106	0.6636	0.2088
Chert/flint	0.010	–	<0.001	0.0036
Quartzite/quartz	0.663	<0.001	–	0.0309
Millstone	0.208	0.0036	0.0309	–

Table 12
Raw material type, proximity, size (mm), and quality for the sites included in this study.

Site	Raw material	Proximity	Cobble/nodule/block size	Mean length	Range length	Mean width	Range width	Quality
BF	Flint	Local	Medium to large cobbles	110.64	70–170	67.4	46–89	Medium
BOX	Flint	Local	Large nodules	115.55	68–161	76.24	47–114	Good
ELV	Flint	Local	Medium to large cobbles and nodules	101.96	67–154	61.34	33–100	Medium
SW	Flint	Local	Small to medium cobbles	98.12	59–172	62.63	30–89	Medium
LN.a	Millstone	Local	Medium to large slabs and blocks	127.68	83–235	77.45	45–138	Good
LN.c	Flint Chert	Imported	Medium nodules	113.47	67–161	67.65	43–93	Good
CLG	Flint	Local	Medium to large nodules	129.21	55–189	73.75	41–115	Medium
MD	Quartz Quartzite	Local	Medium to large beach cobbles	118.33	99–143	73.33	64–91	Medium
	Other metamorphic rocks	Local	Medium to large beach cobbles	121.71	82–159	77.07	59–100	Medium
SP	Flint	Local	Medium to large cobbles	130.75	91–174	74.62	58–100	Medium
ATA	Chert	Local	Medium to large coarse-grained river cobbles;	108.26	57–166	71.05	44–100	Medium to good
	Quartz Quartzite	Local	small Cretaceous chert cobbles; large Neogene chert blocks	108.66	43–163	72.50	38–112	Medium to good
	Other metamorphic rocks	Local		99.03	60–149	66.03	45–91	Medium to good

Abbreviations: BF = Brandon Fields; BOX = Boxgrove; ELV = Elveden; SW = Swanscombe-UMG; LN.a = la Noira stratum a; LN.c. = la Noira stratum c; MD = Menez-Dregan; SP = Saint-Pierre-lés-Elbeuf; CLG = Cagny-la-Garenne (Lower and Upper); ATA = Atapuerca (Galería and Gran Dolina-TD10.1).

some populations survived on the fringes of the region despite the cold climate of MIS 16. Moulin Quignon in the Somme Valley in Northern France has been dated to early MIS 16 and may be an example of population survival and an indication of where population refugia survived to the south of Britain (Antoine et al., 2019). The continued development of technology into MIS 13, and through the severe glaciation of MIS 12 into MIS 11, further implies population survival within or close to the region, suggesting human ability to survive cold conditions between the latitudes of 45 and 50°N. Similar continuity in occupation is implied by the Group 2 sites between MIS 12 and 8. Both Menez-Dregan and Galería have long sequences with similar technological approaches to tool manufacture, suggesting relatively stable populations over long time spans, with potential influence from the LFA of Africa or the Levant. The results also show greater complexity in the Group 1 assemblages from MIS 13 to MIS 11, well-illustrated by the contrasts between Boxgrove, Elveden, and Swanscombe–UMG. This technological complexity fits well with the behavioral changes documented in Europe from MIS 13/11, reflected by more intense occupation, an increased number of sites, and local adaptations (Davis and Ashton, 2019; Moncel et al., 2020b; Ashton and Davis, 2021). Indeed, there is a growing view that there is a common technological foundation in Europe, and that even in the absence of handaxes, the sites form part of an Acheulean technocomplex but with localized expressions of behavior (Mosquera et al., 2013; Ashton, 2015; Moncel et al., 2015; Moncel and Ashton, 2018; Ashton and Davis, 2021). In fact, Groups 2 and 3 should be understood within this new context of diversified technological strategies, using a wide variety of raw materials and with a greater regionalization (Fig. 13).

Within this new scenario, core technology and flake-tool production share many attributes across the continent, but also occasional differences, such as the elaboration of scraper forms at High Lodge in MIS 13 (Davis et al., 2021), or sporadic evidence of early prepared core technology at sites such as Cagny-la-Garenne in MIS 12, la Noira stratum c (MIS 11), and Guado San Nicola during MIS 11/10 (Peretto et al., 2016; Moncel et al., 2021). Some aspects of technology only rarely survive, but were probably practiced on a wider scale (Roebroeks, 2001). These include bone-working (Kretzoi and Dobosi, 1990; Brühl, 2003; Julien et al., 2015; van Kolfschoten et al., 2015; Moigne et al., 2015; Zutovski and Barkai, 2016; Villa et al., 2021), woodworking (Warren, 1911; Thieme, 1997; Schoch et al., 2015), fire-use (Gowlett et al., 2005; Mania, 1995; Roebroeks and Villa, 2011; Ravon et al., 2016a, 2016b; Sanz et al., 2020), and cooperative hunting and efficient hide-processing (Roberts and Parfitt, 1999; Voormolen, 2008; Milks et al., 2016, 2019; Rodríguez-Hidalgo et al., 2017; Milks, 2018; Pedergnana and Ollé, 2020). Although there is little geographical patterning in this scattered evidence, these behavioral patterns probably reflect an underlying foundation of technological capability of European hominins from ca. 500 ka, including handaxe technology, at least in Western Europe, with shared underlying principles of manufacture, but important regional and local differences.

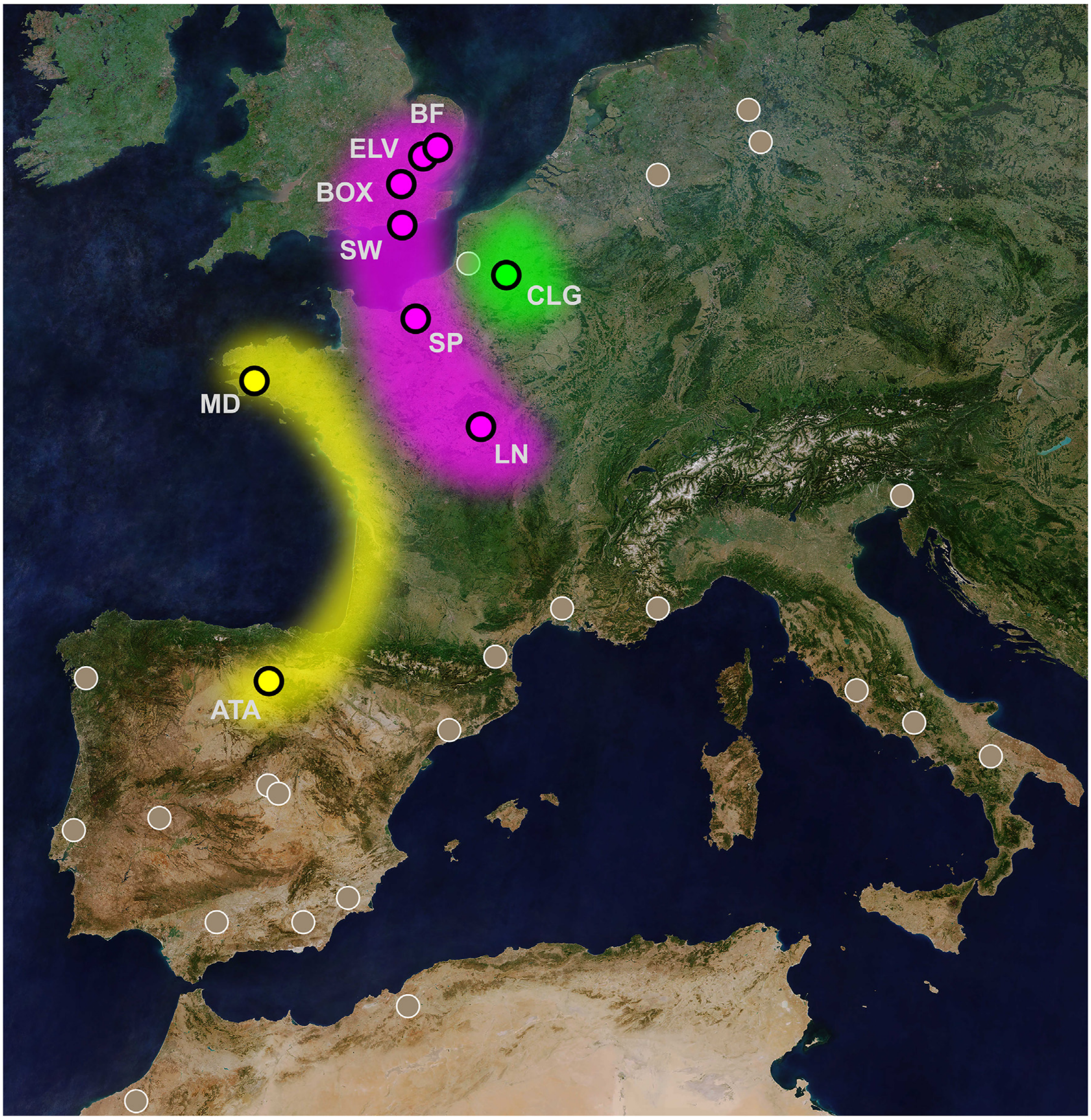

Figure 13. Map with the location of the sites included in this paper, in the context of other Acheulean sites in Western Europe. The coloring of areas corresponds to Group 1 (pink), Group 2 (yellow), and Group 3 (green). Abbreviations: LN, La Noira; BF, Brandon Fields; BOX, Boxgrove; ELV, Elveden; SW, Swanscombe; SP, Saint Pierre-lès-Elbeuf; CLG, Cagny-la-Garenne; MD, Menez-Dregan; ATA, Atapuerca. Map from: https://www.esa.int/var/esa/storage/images/esa_multimedia/images/2018/04/cloud-free_europe/17486453-1-eng-GB/Cloud-free_Europe.jpg. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

5. Conclusions

Handaxes are considered as one of the key elements for understanding human behavior from the past, because of the technological skill required, their variation in form, and their widespread presence. For this study, we have used them to show evidence of population dispersal or continuity and regionalization in tradition. Past attempts to understand handaxe variation on a subcontinental scale have been hampered by regional traditions of lithic analysis, which in this study have been overcome by adopting a unified approach that combines technological analysis with GMs.

The appearance of developed handaxe technology in stratum a of la Noira suggests innovation through cultural diffusion, as no direct antecedents are apparent in other European early Middle Pleistocene sites. In France and Britain from MIS 17/16 to 11, there is little evidence of sudden innovation in handaxe technology, but rather a steady progression of incremental steps and improvements in technique, producing greater control over tool design. Oval shapes clearly predominate in the record until MIS 13. From MIS 11, there seems to be more intense occupation across the continent, which corresponds with local adaptations. The apparent technological continuity implies that some populations survived on the fringes of the region despite the cold climate of MIS 16 and 12. In contrast, along the Atlantic edge of Europe (from MIS 11 to 8), there is the use of a diverse range of raw materials, where a simpler Acheulean technology developed. There is a loss of definition in tool shape, generating more oval and wider forms, and with cleavers playing a significant role. Importantly, there also appears to be continuity in the populations, as shown by the semi-permanent occupation of both Menez-Dregan and the Atapuerca sites. These different regional developments appear to be due to traditions of manufacture through knowledge transfer and continuity in population, rather than simply responses to differences in raw materials. However, the deep complexity of the long-lasting

Acheulean technocomplex, over wide areas, with different raw materials, local adaptations, varied occupation patterns, with cultural connections and disconnections, and coming from a great variety of scenarios makes it essential to enlarge the data set to compare other areas of Southern Europe and North Africa, to analyze data and strengthen these conclusions.

Declaration of competing interest

There is no conflict of interest.

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Appendix A. Supplementary Online Material

Supplementary online material to this article can be found online at https://doi.org/10.1016/j.jhevol.2023.103357.

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