

Innovations in Acheulean Biface Production at La Noira (Centre France): Shift or Drift Between 700 and 450 Ka in Western Europe?

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Abstract

The archaeological sequence of la Noira, in the Middle Loire Basin (Centre region, France) yielded two phases of occupation: ca 700 ka (stratum a) and ca 450 ka (stratum c). No site between these two dates has yet been discovered in the area, and this chronological period has thus been interpreted as a gap in settlement from MIS 16 to MIS 12. Here, we compare these two levels and track technological innovations or/and inventions during this time, based on the technological and morphometric comparison of the Large Cutting Tools (LCTs), applying a new method of analysis. We explore inter and intra-level variability in order to address the hypotheses of (1) the filiation over time of populations settling sporadically in the region or (2) the arrival of new populations from other European or extra-European areas. Stratum a presents mainly short shaping sequences on local millstone, taking advantage of natural slab geometry, and with special attention to tips, but with clear management of tool volume. Stratum c differs in that both local millstone and flints from distant sources show longer shaping sequences, the use of soft hammers for several series of removals, combined with final regularizing retouch on entire edges. The morphometric approach shows a morphological transition from oval to teardrop shapes for the thinnest tools. A technological filiation between strata a and c and between la Noira populations from MIS 16 and MIS 12 in this area has to be considered.

1. Introduction

At the end of the Middle Pleistocene Transition (MPT) in Western Europe, after the Brunhes-Matuyama reversal (780 ka), climatic cycles changed, leading to significant variations in resources. These cycles must have affected the extinction/relocation of small groups of hominins, and subsequent recolonizations, between the two long MIS 16 and MIS 12 cold events (1–12). MIS 12 was followed by a long interglacial stage (MIS 11) which marks the beginning of new behaviours and the advent of the Neanderthal technical world (13). After the MIS 12 glaciation, considered as a major crisis for hominins, archaeological records show a high quantity and variety of occupations, new subsistence behaviours and important technical innovations (e.g., Levallois technology, increase in light-duty tools and use of fire), and evidence of an early regionalization of traditions (13–15). These behavioural changes suggest increased cognition with new skills and social interactions (16–19).

Among other kinds of behavioural innovations, the Acheulean has been traditionally defined by the emergence of a new tool with bifacial management of volume: the handaxe (20, 21), which has been considered as evidence of new skills and changes in human cognition (22, 23). Due to the effectiveness and the versatility of this type of instrument, handaxes persisted for more than 1 Ma over a vast geographical area (24). This tool first appeared in East Africa around 1.75 Ma, but is not present in Western Europe before 900 ka and especially from 700 ka onwards (ref). In spite of apparent technological stability, this kind of instrument encompasses huge variability in terms of production, as well as in terms of the morphological outcome of shaping processes. Strata a and c of the la Noira site, located in the centre of France, and the large corpus of handaxes are appropriate case studies for tracking technological behaviours common to both levels and identifying innovations/inventions over time. We aim to discuss two crucial phases of hominin settlement in Western Europe but also to contribute to hypotheses positing either a filiation between European populations over time or arrivals of new populations introducing new skills after MIS 12. By *inventions*, we mean evidence of technological breaks with previous tradition(s), while *innovations* refer to internal behavioural evolution rooted in the past and sometimes motivated by external or internal changes. Common features between the two phases of occupation and existence of innovations rooted in the past would point to a possible filiation over time of populations between the MIS 16 and MIS 12 glacial periods and would imply that these populations were able to return to abandoned areas when the climate was favourable, aided perhaps by more complex behaviours due to internal evolution and increase of skills (25).

The site of la Noira is located in the Middle Loire Basin (Centre region, France), on the western slope of the Cher River Valley (26) (Fig. 1). Five successive sediments strata can be observed at the site (from bottom to top): a coarse slope deposit (stratum a), covered by two sequences of sandy alluvial layers (stratum b), diamictons of pebbles with frost shattered debris and coarse colluvia (stratum c) and the a washed sandy-silty soil (stratum d). This paper focuses on the oldest archaeological level (henceforth referred to as the 'lower level'), located in stratum a, while the younger upper level is located at the top of stratum c.

The lower layer (stratum a) was deposited on the limestone bedrock at the beginning of a glacial stage after river incision. The slope deposits contained local lacustrine millstone slabs, some of which were selected by hominins for knapping and shaping. Occupations were located on the river bank. The age of fluvial formation was determined using the ESR method applied to optically bleached sedimentary quartz grains. The mean ESR age value obtained for the sandy formations of stratum b is 655 ± 55 ka. Tests with cosmogenic nuclide dating provide a similar value of 730 ± 210 ka, but with an excessively high margin of error (27). The average age of the human occupation is thus around 700 ka (26). The hominin occupation occurred between the end of river incision and the fluvial deposits, suggesting that hominins were present during the beginning of the MIS 16 glacial stage, just before the pleniglacial fluvial depositions. They left the area during the early glacial MIS 16 at around 670 – 650 ka, when cold conditions became too rigorous (14, 28).

The petrographic composition of the sediments of stratum c (composed of three sub-levels) is identical to that of the lower stratum a, composed of sands and quartz gravels with endogenous pebbles (granite and quartz) and sedimentary siliceous rocks. The ESR date of 449 ± 45 ka indicates that diamicrons of stratum c could have been deposited at the end of the MIS 12 glacial (frozen cracks soil and frost debris) and mainly during the MIS 11 interglacial (eroded soil and deep channels). The remarkable preservation of the artefacts could indicate that they were not affected by frost as they were overlain by thick colluvial deposits (29–32). While local millstone was the only raw material used during the early occupations, the stratum c assemblage is composed of 30% of flint and silicifications transported from long-distance Jurassic and Cretaceous outcrops, between 50 and 100 km from the site (33).

In recent decades, new dating and excavations have been conducted to identify gaps in human occupations in Western Europe (14). The Centre region of France is one of the areas where two gaps have been documented, one between 1 Ma and 700 ka and a second one between 700 and 450 ka (26), possibly explained by climatic factors due to the location of the area beyond the 45th parallel. In Western Europe, few sites can be used to investigate such gaps in human occupation. La Noira is one such example (14, 28). The technological analysis of all the lithic material from stratum a at La Noira has already enabled us to explore (13, 14, 28) the onset of the Acheulean at 700 ka in Western Europe and the technological skills of these hominins. A specific morphometric analysis of handaxe symmetry in strata a and c (32) has shown that human groups mastered tool symmetry from 700 ka onwards, despite lower shaping intensity at that time. In order to continue to track the technological drift between ca 700 and ca 450 ka, we applied the WEAP method (34) on the whole corpus of handaxes of this site, combining for the first time a technological analysis with a broader morphometric approach using AGMT3-D software (35, 36).

2. Results

The studied corpus is composed of 31 handaxes for stratum a and 47 handaxes and cleaver-like tools (bifacial tool with a round or transverse extremity) for stratum c. They were collected *in situ*, and come from recent excavations and systematic surveys carried out for the three last decades in the quarry. All the handaxes from the lower level (stratum a) are made on local millstone slabs, and in nearly 65% of cases, slabs are only used for shaping. In the upper level (stratum c), our corpus of tools is shaped on comparable proportions of millstone slabs (48.94%) and flint nodules (51.06%, Fig. 2). For 34% of the series, it was impossible to identify the type of blank, due to invasive shaping.

Table 1
Number (N) of LCTs and frequencies (%) in stratum a and stratum c, raw material type and type of blank.

	Stratum a								Stratum c							
	Slab		Flake		Unknown		TOTAL		Slab		Flake		Unknown		TOTAL	
	(N)	%	(N)	%	(N)	%	(N)	%	(N)	%	(N)	%	(N)	%	(N)	%
Millstone	20	64.52	7	22.58	4	12.90	31	100.00	11	47.83	5	21.74	7	30.43	23	48.94
Flint & silicific.	-	-	-	-	-	-	-	-	7	29.17	8	33.33	9	37.50	24	51.06
TOTAL	20	64.52	7	22.58	4	12.90	31		18	38.30	13	27.66	16	34.04	47	

The combination of the technological features (Table 1, Supplementary Information Tables 1–4) in a multivariate approach (Principal Component Analysis) indicates that technological differences exist between the two levels (Fig. 1). This PCA accounts for more than 66% of the variability of the series. PC1 (43.11%) divides the samples according to level, whatever the raw material (millstone or flint) or type of blank (slab, flake or nodule).

2.1. Stratum a

All the handaxes are made with hard hammers (58.06%) or with a combination of hard and soft (32.26%) hammers, especially on tool extremities (Fig. 3). The tips appear much more worked and retouched than the cortical butts (more than 83%). Tool edges are mainly sinuous (48.39%) and the profile is non-symmetric (80.65%). The high variability of the corpus is mainly due to the type of *façonnage* of the tips. For more than 50% of tools, we observe one or two face by face or alternate series of removals. Less than 50% bear final retouch, and retouch is absent from lateral and proximal cutting edges. Removals affect the edges either marginally (51.61%), producing regular edges, or more intensely (48.39%), generating more denticulate and irregular plan-shape profiles. When only one series of removal exists, it is non-invasive over the tool surface. When there are several series of removals, shaping is more invasive, and can extend up to the midpart of the tool surface. In nearly 40% of cases, there is a combination of an invasive first series of removals and a second series along the tool edges.

Butts retain 40–90% of the original cortex for more than 45% of tools. When removals are present, they are concentrated on butt edges. Finally, the corpus of Large Cutting Tools (LCTs) from stratum a presents high shaping variability with a significant difference in the management of tips and butts. Tips present more careful treatment, sometimes with final retouch while butts remain mainly cortical (Suppl. Inform., Fig. 1, lower part).

The only exception to this high variability concerns pieces on unknown blanks (13% of tools). The PCA shows how this category of tools is clearly affected by the PC2 (23.14%) (Suppl. Inform. Figure 2). They differ in that they are characterized by longer operative chains with two series of removals, the first one invasive and the second one short on both the tip and the upper part of the tool, followed by final retouch only on the tip. In both cases, hard and soft hammers are used. The butt is less cortical (40%) and shaped by only one invasive series of removals by hard hammer percussion.

2.2. Stratum c

The corpus from stratum c includes handaxes and some 'cleaver-like' handaxes (handaxes with wider convexity on tips, generating a sort of transverse end). The tools mainly show higher standardization with longer operative chains and significant blank reduction (Fig. 4). Shaping extensively affects the entire tools with evidence of the use of hard and soft hammers on the whole piece. The presence of cortex is limited to the butts or part of the lower surface and the tips have no cortex (89%). 23% of tools bear no cortex. The tools present mainly non-symmetric profiles but the proportion of symmetric tools increases (up to 20%) with rectilinear edges (54%). The use of soft hammers (around 60%) is clearly visible on all the sectors of the tools (tip, mid and butts). For 49%, dense final retouch obliterates the last removals. For 27.66% of the tools, the tip is shaped by two series of removals, combining invasive and non-invasive scars. Final retouch can extend to the midpart of the tool surface or can be limited to the edges. Finally, for 17% of cases, we also documented a *coup de tranchet* removal with a non-retouched distal edge.

The midpart of tools is above all worked by two series of alternate removals (63.87%) with final retouch and without cortex (28%). Like in stratum a, this type of shaping profoundly modifies edges. Nevertheless, for this level, we observe a change in shaping strategies mainly for tools on millstone slabs. The edges are more regular, with a combination of a first invasive series of removals, followed by a non-invasive second series and finally, marginal retouch confined to the edges. Butts are non-cortical or with small patches of cortex. In 92% of cases, there is only one series of removals and marginal use of a soft hammer, mainly on tools shaped on flakes.

2.3. Stratum a vs stratum c LCTs

The Principal Component Analysis defines the existence of two clear groups of tools: strata a and c (Fig. 5). The differences are independent of the type of raw material (millstone and flint) and the type of blank used for shaping (slabs, flakes or nodules). The distance between strata a and c shows rather a technological origin, possibly related to a change in shaping strategies. The first main difference between these groups is that sequences are more diversified and shorter for stratum a tools, and longer and more standardized for stratum c tools. In addition, out of the whole set of technological features considered here, the presence of original cortex (Fig. 5A) and the different combinations of series of removals (Fig. 5B) have a major effect on the distance between these two assemblages (Suppl. Inform. Figure 1 and Fig. 2), which is also visible by Cluster analysis (Fig. 5C). Handaxes in stratum a present cortex on 50% of tools (butt and mid parts), and sometimes covers the whole instrument. In stratum c, there is an increase in the ratio of non-cortical tools, as well as in the use of final retouch, independently of the type of blank used. PCA also points to a clear differentiation of tools from stratum a, which present longer shaping sequences and unknown or indeterminate blanks (Unkn). They are clearly apart on the PCA graph and are represented as an independent branch of the Cluster. Tools from stratum c show a different pattern, reflecting a certain association between raw material and blank type. Millstone is mainly associated with what slabs, and flint types present the same technological features as handaxes made on unknown blanks. Flakes appear as an independent group, regardless of raw materials.

The results of the geometric morphometric analyses of tools from strata a and c of la Noira indicate the extent of intra-group shape variability, expressed as the mean multidimensional Euclidean distance of all items of a group from its group centroid. Overall, the groups considered are fairly similar (Fig. 6) but tools from stratum a present higher variability. The most homogeneous group is composed of millstone tools from stratum c. The distribution of the total standardized coefficients across the three dimensions X, Y and Z shows differences in relative width, length and thickness respectively (Table 2). In the archaeological assemblages, most of the variability corresponds to differences in relative thickness, mainly in stratum c and specifically for millstone tools. On the other hand, the tools from stratum a show higher variability in width and length.

Table 2

Intra-assemblage shape variability (measured as the mean multidimensional Euclidean distance of all artefacts from its centroid) and distribution of relative shape variability across dimensions (calculated as the proportion of variability in each homologous semi-landmark coordinate for each specific dimension).

		<i>variability (%) caused by</i>			
	(N)	Shape variability	x (width)	y (length)	z (thickness)
Stratum a	31	348.42	47.73	5.97	46.30
Stratum c	47	321.2	38.85	4.84	56.31
Millstone_a	31	348.42	47.73	5.97	46.30
Millstone_c	23	308.90	37.60	3.52	58.88
Flint_c	24	325.75	40.36	5.89	53.74

Figure 6 displays a PCA scatter plot of the first two PC, showing 32.50% of the entire shape variability of the whole sample, including 95% confident ellipses and centroids (corresponding to mean shapes). PC1 (22.13%) indicates the difference between oval vs pointed shapes. PC2 (10.13%) shows the difference between the localization of the main thickness of the tool and the convexity of the butt (mid-upper part or mid-lower part). Shape distribution is fairly homogeneous but some differences are visible. Tools from stratum a present a trend towards oval shapes, with maximum thickness located on the midpart of tools. On the other hand, tools from stratum c present a tendency towards pointed shapes, with maximum thickness on the mid-proximal part of the pieces and a significant reduction in distal width and thickness.

Geometric morphometric shape analyses quantify these differences using a single value, representing the multidimensional Euclidean distance between the means of each group. Together with the results of the Wilcoxon Rank-sum test on the inter-point distances between the means of each group and the items in the opposite group, it shows that differences between the two strata are statistically significant ($n_1 = 32$, $n_2 = 39$, ranksum = 4128, $p = 0.01$), even for the same raw material (millstone $n_1 = 32$, $n_2 = 18$, ranksum = 2086, $p = 0.01$). If we compare raw materials in stratum c (millstone and flint), differences are not significant ($n_1 = 18$, $n_2 = 21$, ranksum = 1454, $p = 0.39$). The same results are obtained applying the MANOVA test on the first 10 PC (Table 3). The greatest differences emerge from comparisons between the two phases of occupation, as stated by Wilks' lambda Test = 0.40; $df_1 = 20$; $df_2 = 118$; $F = 3.44$; $p = 0.001$, and the most similar groups are millstone and flint tools of stratum a.

Table 3

MANOVA analysis on first 10 PC scores (74% of variance) from Fig. 7, between stratum a and stratum c from la Noira and raw materials.

	Stratum a Millstone	Stratum c Flint	Stratum c Millstone
Stratum a Millstone		0.0001069	0.0002223
Stratum c Flint	0.0001069		0.6544600
Stratum c Millstone	0.0002223	0.6544600	

Tool size and thickness decrease from stratum a to stratum c (Suppl. Inform, Table 5). Millstone and flint tools from stratum c present nearly the same values, indicating common strategies, regardless of the stones and their natural geometry. In addition, we must point out significant variation in distal vs proximal length. In stratum a, proximal length is higher, while in stratum c, distal length is higher (Fig. 7A). This is consistent with the geometric morphometric analysis and the contrast between oval shapes in stratum a, with longer bases, and more pointed shapes, with longer distal parts in stratum c.

Through the analysis of six angles measured along each edge, we document more acute angles on the mid-distal part, and wider angles on the mid-proximal part, in both strata (Fig. 7B, Table 4). However, in stratum a, due to the lesser degree of edge shaping standardization, most of the angles are between 45° and 80° along the whole edge, and only some tips extend beyond this range. In stratum c, where a predominant use of soft hammers is associated with longer sequences, we observe a significant change in angles. The angles of the cutting edges are more acute, homogeneous and differ between the distal and the proximal sectors of the tool. Tip angles are between 30° and 45°, mid part edge angles between 40° and 70° and butt angles between 60° and 80°.

Table 4
Descriptive statistics (mean and standard deviation, SD) and coefficients of variation (CV) for the six edge angles considered, for strata a and c of la Noira.

		Distal	1/5	2/5	3/5	4/5	Proximal
Str. a	Mean	46.87	59.29	66.7	71	75.38	74.4
	SD	13.69	11.22	9.82	11.18	11.2	16.11
	CV	0.29	0.18	0.14	0.15	0.14	0.21
Str. c	Mean	34.22	50.00	60.26	64.94	68.28	73.74
	SD	7.38	10.86	12.74	11.05	12.01	16.09
	CV	0.21	0.21	0.21	0.17	0.17	0.21

The Scar Density Index (SDI) in relation to tool volume is coherent with the technological and morphometric analysis (Table 5). This ratio is higher for tools from stratum c, as well as for tools made on an unknown blank in stratum a. Therefore, the longer the shaping process, the higher the ratio between SDI and volume. But this also implies that the higher variability and lower standardization of the handaxes from stratum a has a clear effect on this result (Table 2). For raw materials, we can see the same pattern, between flint tools, which present the highest ratio, and millstone handaxes with the lowest ratios.

Table 5
ANOVA statistical test between SDI values and volume according to raw material type and the type of blank between strata a and c of la Noira.

		N	F	p	r ²
Stratum a	Millstone	31	11.07	0.01	0.27
	Slab	20	7.03	0.01	0.28
	Flake	7	1.69	0.25	0.25
	Unknown	4	5.34	0.1	0.72
Stratum c	Millstone	20	6.73	0.01	0.27
	Flint	21	13.85	0.01	0.42
	Slab	15	3.42	0.01	0.20
	Flake	11	6.79	0.01	0.42
	Unknown	15	15.44	0.01	0.54

The statistical analysis of the degree of symmetry of tools shows that the main differences are between millstone handaxes from stratum a and stratum c. We note an increase in bilateral symmetry with an average of 25% (Table 6). Wilcoxon rank sum tests confirm that this difference is statistically significant (n1 = 32, n2 = 18, ranksum = 916, p = 0.04). In terms of bifacial symmetry, there is an increase of nearly 35% throughout the sequence, which is statistically significant (n1 = 32, n2 = 18, ranksum = 968, p = 0.01). The edge irregularity test shows that, in all cases, both edges of the same tool are always different. Nevertheless, as bilateral and bifacial symmetry show higher diversity for millstone tools from stratum a, flint tools present more regular edges. As mentioned previously, the main difference between the tools from the two strata is the combination of several series of removals (duration of shaping processes). In the case of flint, there is often a third series, and final non-invasive retouch on the cutting edges (Fig. 4D). This has a clear impact on the regularity of the edges (profile symmetry). Nevertheless, the main difference between the millstone handaxes in the two strata is the massive use of at least two series of removals on the midparts and butts of the tools from stratum c, which dramatically reduces tool thickness. Bilateral and bifacial symmetry (plan shape symmetry) is thus affected.

Table 6
Summary statistics for deviations from perfect bilateral and bifacial symmetry and edge irregularity.

		Stratum a		Stratum c
		Millstone	Flint	Millstone
Deviation from perfect bilateral symmetry	Max	19.82	13.61	9.41
	Median	6.08	5.50	5.07
	Min	2.62	2.36	2.93
	Mean	7.06	5.66	5.17
	Std Dev	3.49	2.72	1.52
Deviation from perfect bifacial symmetry	Max	15.27	11.81	6.58
	Median	6.05	5.13	3.38
	Min	2.81	2.11	2.48
	Mean	6.18	5.12	3.99
	Std Dev	2.79	2.21	1.28
Left edge irregularity	Max	319.46	188.68	162.02
	Median	109.44	83.80	76.12
	Min	41.31	48.43	39.88
	Mean	124.76	86.16	85.06
	Std Dev	69.16	34.14	35.01
Right edge irregularity	Max	293.25	200.22	229.58
	Median	97.96	89.21	107.79
	Min	51.78	26.54	45.37
	Mean	122.99	90.81	112.68
	Std Dev	64.37	46.50	49.11

3. Discussion

The Early Pleistocene is marked by climate cycles of 41 ka, leading to temperate and more open conditions during glacial to interglacial transitions (5–7, 37–44). More open environments were favourable to human colonization. During the Middle Pleistocene, the shift to c.100 ka climatic cycles, designated as the Middle Pleistocene Transition (MPT) (2, 4, 45, 46), led to more extreme conditions which could have profoundly impacted human populations and dispersions, and may explain possible successive depopulations or extinctions of small groups of hominins during cold events in the north, necessitating re-colonization from the south during warmer events (47). The second climatic transition (Mid-Brunhes Event-MBE) between MIS 13 and 11, with more marked glacial–interglacial cycles might explain in part the wider diffusion of the Acheulean through Western Europe during warmer interglacials and the extension of the mammoth steppe in the northwest from 500 ka (48, 49). For north-western Europe, evidence suggests occasional dispersals, which would account for the diversity of strategies due to regular introductions of new behaviours and populations. Gaps are also recorded in southern Europe. At Atapuerca, for example, an occupation hiatus is observed between 800 and 500 ka (6, 50), which is similar to the hiatuses observed in the centre of France, between 1 Ma and 700 ka and 700 to 500 ka (26).

In Early Acheulean African assemblages, for example, Olduvai, Bed II (1.5 Ma), Gadeb (1.7–1.5 Ma to 0.8 Ma) or Peninj (1.6–1.5 Ma), in East Africa, tools are mainly pick-like with flat or triangular cross-sections and little overall volume management. These tools are associated with minimally shaped LCTs on cobbles and flakes, unifaces and a large diversity of other types of heavy-duty tools (51–54). A technological shift is then recorded at c. 1 Ma with the development of the use of soft hammers, together with a higher ratio of more standardized handaxes (55–58). Whatever the origin of Acheulean behaviours in Europe, similar technological and morphometric changes

are also recorded over time in the assemblages. Stratum a of la Noira attests to the mastery of biface production, with the management of volume and tool symmetry, assisted in some cases by the use of soft hammers, mainly on distal parts (14). These features justify the hypothesis of a well-established Acheulean tradition at c. 700 ka in Western Europe (13, 14, 28). Coupled with a geometric morphometric analysis using 3D models, this technological study of the LCTs tracks for the first time innovations v. common features and the degree of filiation between strata a and c for the heavy-duty component. Our method enables us to determine a large set of similar and different tool features related to shaping modes and final morphometry.

Data clearly distinguish the two different technological assemblages (stratum a and stratum c), regardless of raw material or blank types. In stratum a (13, 14, 28), a single local raw material is used, millstone slabs. Handaxe shaping retains large cortical surfaces and exploits stone geometry with one or two series of removals, mainly with hard hammers. This behaviour generates a few standardized assemblages. Nevertheless, technological control of the tips is also observed, using both hard and soft hammer percussion. We can also mention evidence of longer shaping chains on some tools (group of unknown blanks). On the other hand, stratum c is characterized by the use of diverse stones and the introduction of raw materials from long-distance areas. The use of local stones in stratum c indicates an increase in the size of the procurement zone, suggesting higher mobility for hominin groups at the end of MIS 12 and the beginning of MIS 11. The large majority of tools in this level present long reduction sequences, with at least two series of removals and final retouch, thinner tools, a widespread use of soft hammers on the whole tool, and less extensive cortical zones.

The tools made on indeterminate blanks in stratum a, with longer operative chains, are key to point to a possible filiation between the two levels. What was original and occasional in stratum a became generalized in stratum c. These new features also include the generalization of the use of soft hammer percussion and the widespread use of final retouch. Finally, an intensification of the technological features documented in the lower level is only observed on some pieces and a local raw material. This results in higher heterogeneity in tool cutting edge angles in stratum a, while in stratum c, more careful management of tool thickness and edges leads to increased homogeneity and more acute angles. In addition, the values of the angles between tips (30–45°) and butts (60–80°) are differentiated.

From a morphometric point of view, there is a transition between the two levels from oval (globular) shapes and few standardized tools, with the maximum width of the tool at mid-length, to 'teardrop' shapes in a more homogeneous assemblage, with the maximum width of the tool at the base (Fig. 8). There is also a transition from short distal parts, with wider convex tips, to longer convergent edges with more pointed tips, opposed to wider bases. In addition, intense technological work on the tools of stratum c results in reduced tool thickness. As Iovita et al. (2007) stated, Acheulean toolmakers had the technical abilities and skills to produce symmetric tools from 700 ka onwards. Nevertheless, there is an increase in this tool symmetry in stratum c. Iovita et al. (2007) concluded that this symmetry was dependent on the degree of reduction and the raw material. The use of 3D models in the geometric morphometric analyses led us to go further and clarify this conclusion. Bilateral and bifacial symmetry increase on average by 25% and 35% respectively. Plan symmetry is mainly affected by the *façonnage* strategy, by more than one series of removals on the whole perimeter of the tool, reducing the thickness and modifying the original geometry of the blank whatever the raw material. Nevertheless, edge regularity depends on final edge retouch.

How should these differences between the two occupation phases be interpreted? Do they stem from local or on a broader scale innovations rooted in the past motivated by external or internal changes or do they represent a shift, inventions as a result of a break in populations with new dispersals?

At la Noira, our analysis highlights two main features. First, in stratum a, we do not observe any differences in shaping or in morphological results for different blank types, even if slabs predominate. Only some tools with longer sequences stand out from the rest of the corpus (n = 4, 12.9%) due to more intense shaping, making it impossible to identify the type of blank. The tools present a combination of soft and hard hammer percussion and more intensive final retouch. Consequently, the hominins of stratum a were able to develop complex and versatile operative chains.

Should we consider that this ability at 700 ka is evidence of a technological filiation between populations from MIS 16 to MIS 12? If we look at the results of the geometric morphometric analysis, we do not observe real morphological breaks between the two corpora. Handaxes from stratum a are not homogeneous and short shaping sequences are correlated with greater tool thickness. Morphometrically, the complexity of this biface production at 700 ka is observed in the ability to manage tool plan shape for oval shapes, placing the centre of the mass at the midpart of tools. The stratum c corpus is characterized by a higher standardization of shapes, creating wider bases opposed to thinner and more pointed tips. The use of several series of removals reduces tool thickness. We observe total control of volume and edge morphology, which become more regular. A filiation between the populations at la Noira is thus possible, suggesting that the long interglacial MIS 11 in Western Europe was not really a threshold and enabled local and European populations to re-occupy abandoned areas when the climate became more favourable, facilitated by demographic expansion and the implementation of more complex strategies.

4. Methods

We applied the WEAP Method to 78 handaxes and cleaver-like tools from stratum a and stratum c as part of a detailed technological and morphometric study aiming to analyse final tool variability. The WEAP method was developed in the context of a Marie Skłodowska Curie IF-EF-ST Fellowship (IP: 748316) devoted to investigating the variability of Acheulean industries in Europe (34). This method considers each Large Cutting Tool (LCT) from two points of view. 1) As a single unit, including aspects such as raw material type, blank type, facial shaping, cortex presence, edge delineation, profile symmetry, number of scars). 2) As the sum of the different parts, each of which are analysed independently, defining the type of hammer used, number of removal series, depth of scars on edges, invasiveness of each removal series, and type of shaping (Fig. 9). Combining all these features, a Multivariate Analysis (PCA) identifies the differences and similarities of LCTs from both levels, comparing raw materials and types of blank.

To complete the technological analysis, we also applied the Geometric Morphometric analysis to describe tool shape with 3D models. All the tools were scanned using a laser scan (DLP projector) and Flexscan software (LMI technologies), transferred from the Fragmented Heritage Project (University of Bradford). All models are available for scientific and academic purposes at ZENODO (35). The 3D models were processed using the AGMT3-D software (36, 37). This consists of a data-acquisition procedure for automatically positioning 3D models in space and fitting them with grids of 3D semi-landmarks. In fact, each point of the grid consists of two semi-landmarks, one placed on each face of the artefact, so that a 50×50 grid provides 5,000 landmarks (Fig. 10A). The top and bottom latitudes capture the exact 3D outline of the artefact's distal and proximal ends. Therefore, this protocol provides a list of landmarks that accurately express the artefact's volumetric configuration. It also provides a number of analytical tools and procedures that enable data processing and statistical analysis (36). For this paper, data obtained with 3D models are presented.

The multivariate outline data were projected into two dimensions so that the underlying shape variables could be qualitatively examined and compared. In order to interpret the Principal Component Analysis (PCA) results from a morphological perspective, Procrustes superimposed shape data were examined using thin-plate splines to facilitate the visualization of shape changes from the group mean along relative warp (i.e., principal component) axes (60). By examining the morphological deformations and XY plots of specimens from the PCA scatters, it was possible to interpret shape variation by itself, without the size effect, and compare the different tools within a site or between different sites. In addition, the derived principal component scores also allowed for the application of other quantitative tests of multivariate equality of means between the groups (36, 37, 61).

The latest version of this software also offers different quantitative approaches to the analysis of specific variations in shape. Firstly, we will use the surface analysis (in^2) and volume (in^3) data to apply a quantitative approach to reduction intensity. The Scar Density Index (SDI, 62–65) has been defined as the number of flake scars (greater than 10 mm in maximum dimension) divided by the surface area. As García-Medrano et al. (2019) noted, a loss of information during the knapping process, contrasting this value with volume information, could establish a useful relationship between the number of scars and tool size.

Lastly, the landmark data were used to calculate the degree of deviation from perfect bilateral (Fig. 10B) and bifacial symmetries (Fig. 10C), as well as the edge section regularity (Fig. 10D) of each item in the sample (37). For bilateral symmetry, this 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 symmetrical objects.

Declarations

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Author contributions statement

The three authors contributed to this work. M.H.M. and J.D. directed the excavation work. P.G. and M.H.M. analysed the materials and wrote the paper. P.G.M took all pictures and 3D models. All authors reviewed the manuscript.

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Figures

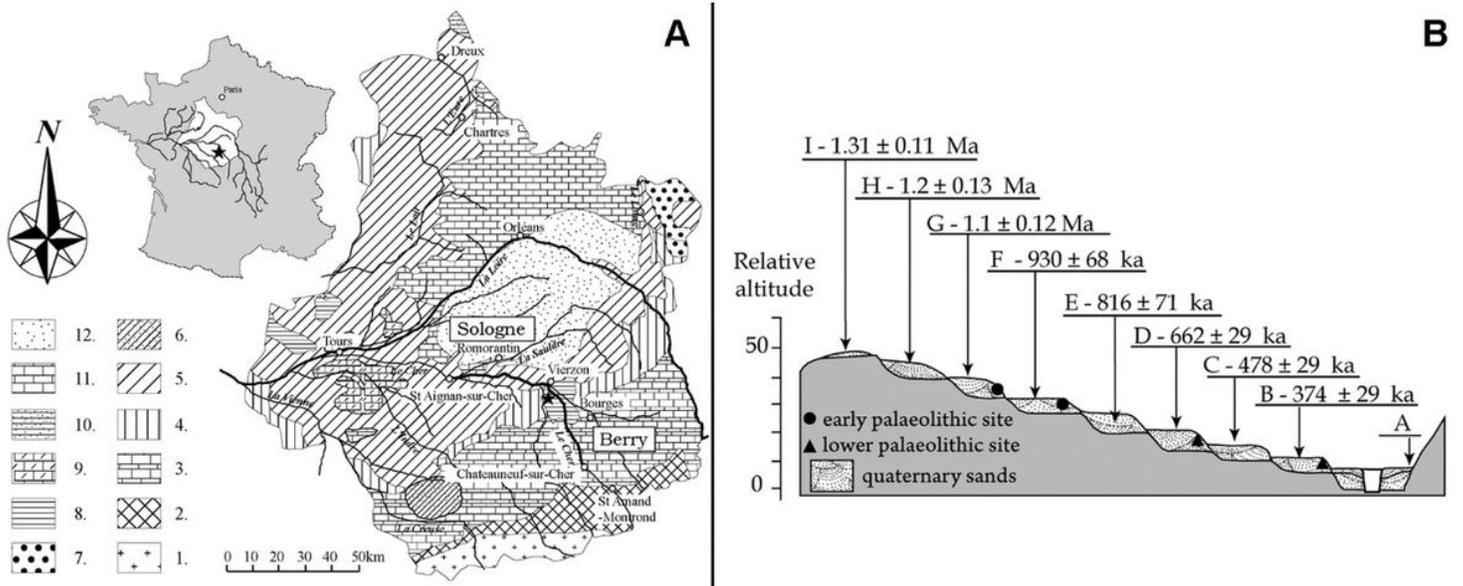


Figure 1

A) Simplified geological map of the Berry Region. B) Schematic stratigraphic section of the upper part of the western section of La Noira quarry: Sandy beds and erosional surface of stratum b, superposition of strata c and d with location of Acheulean artefacts and ESR samples.

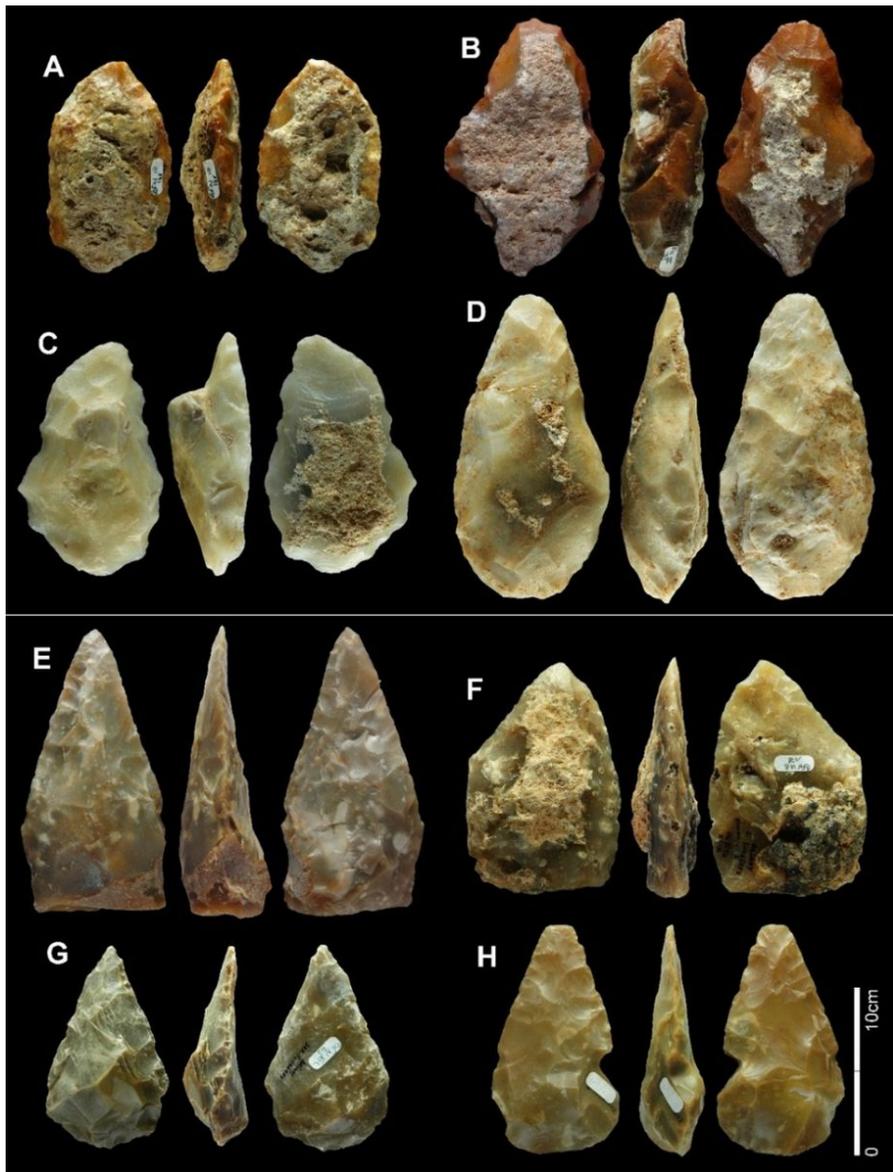


Figure 2

Handaxes from la Noira, stratum a (A, BFN III 146; B, BFN III 39; C, BFLN E1 d2 2; D, BFLN 0C5 d1 1) and stratum c (E, BFN SN; F, BFN VI 62; G, BFN VIb 178; H, BFN VIc 45).

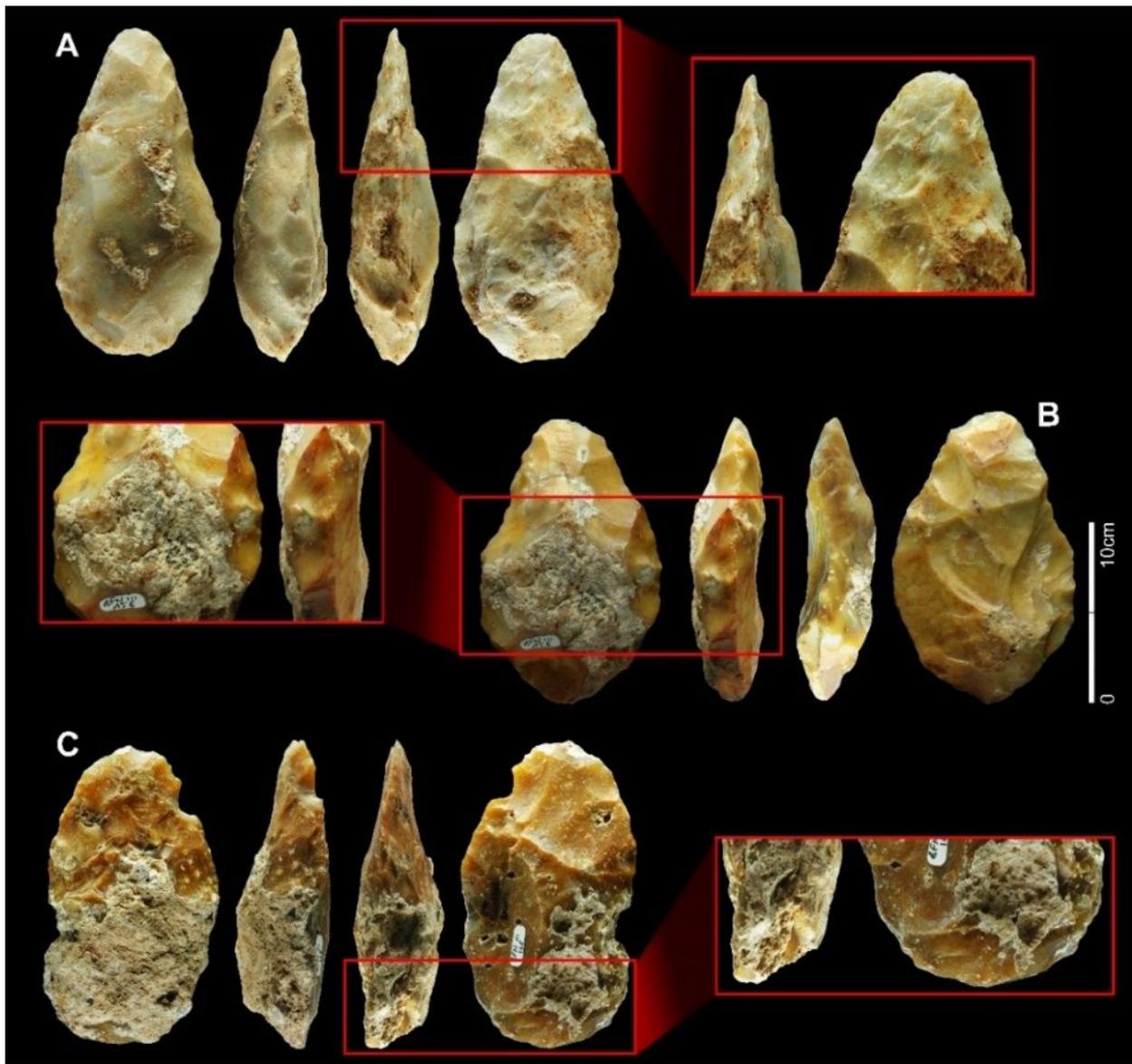


Figure 3

Technological characteristics of handaxes from stratum a of la Noira (A, BFLN 0C5 d1 1; B, BFN III 156; C, BFN III 148).

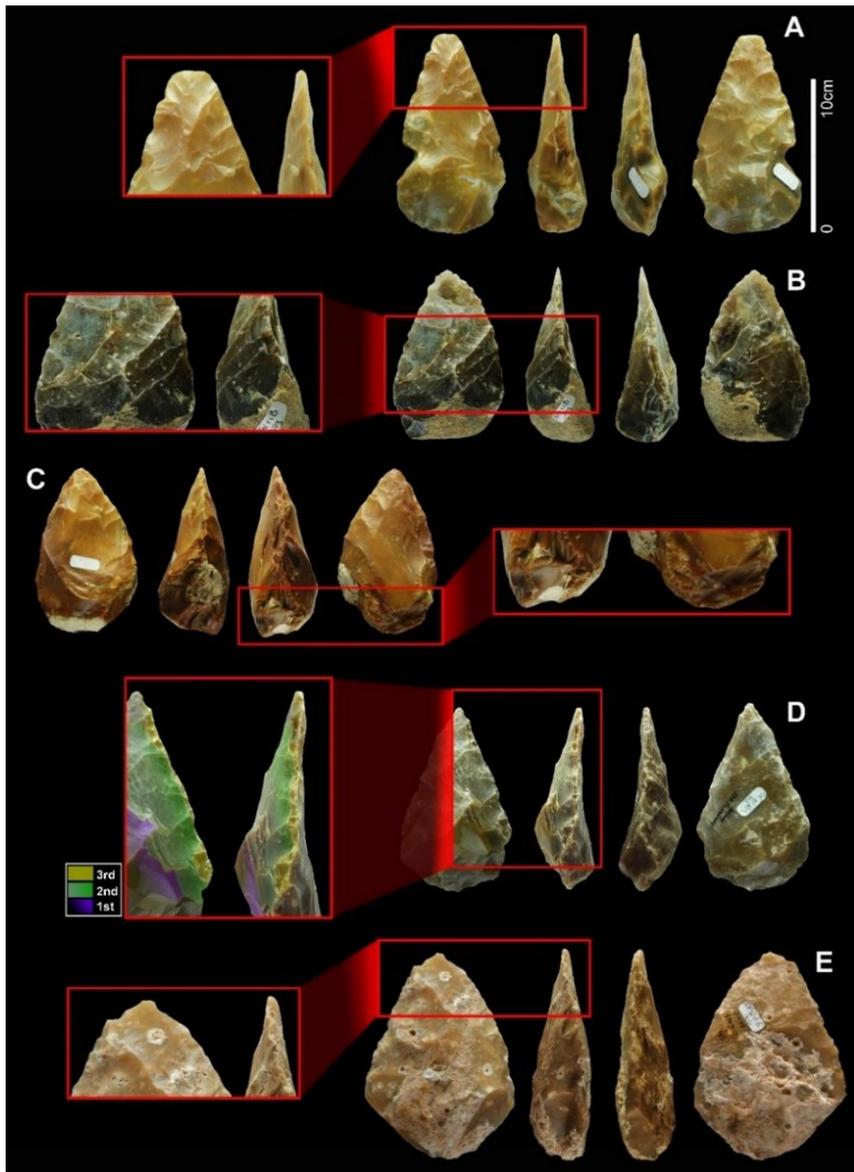


Figure 4

Technological characteristics of handaxes from stratum c of la Noira (A, BFN VI 62; B, BFN Vb 179; C, BFN VI 22; D, BFN Vic 45; E, BFN Vlb 304).

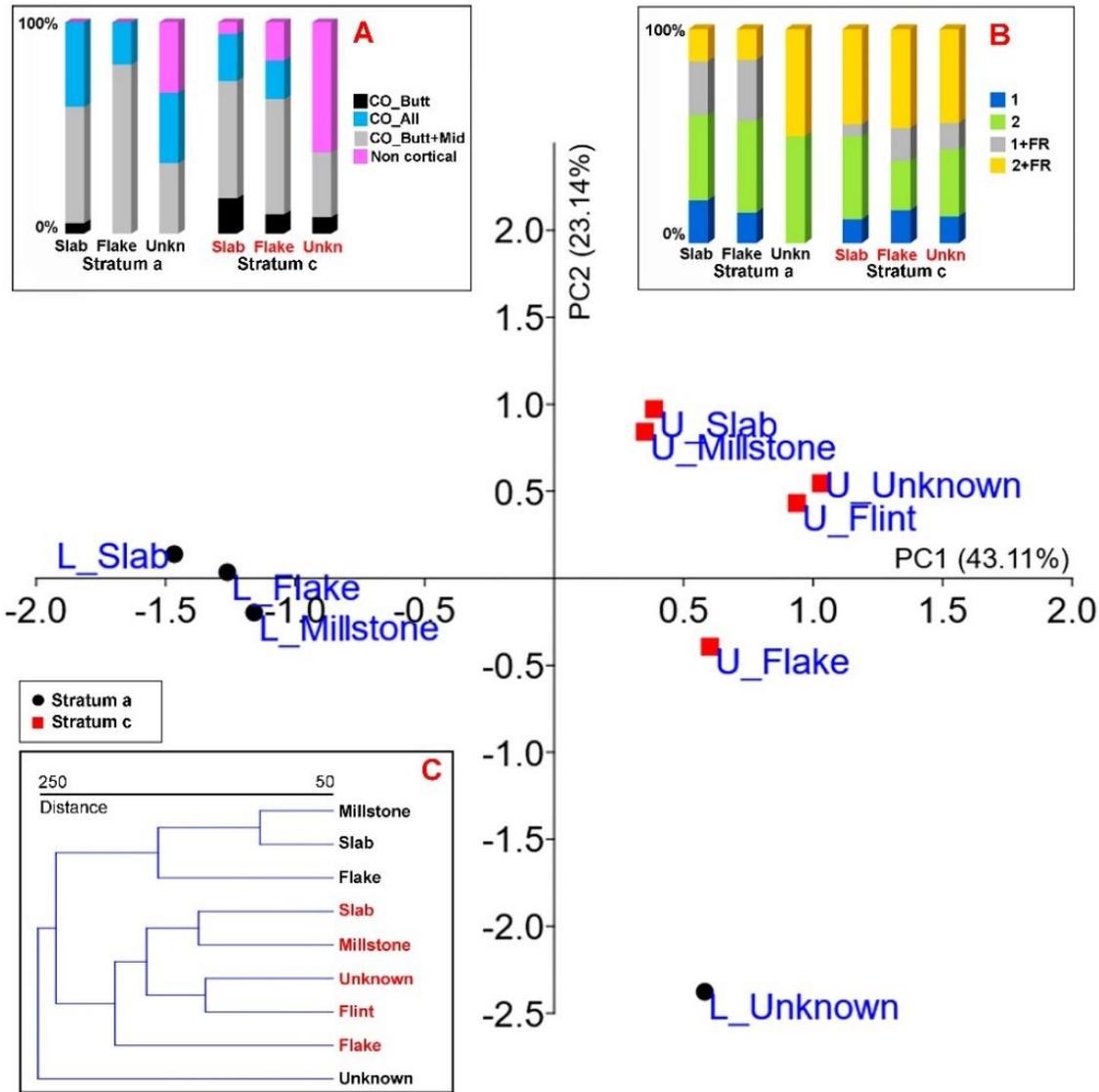


Figure 5

Principal Component Analysis of the technological features considered for the analysis of handaxes and cleaver-like tools: Handaxe as a single unit (A); Handaxes as three different parts (Tip, B; Midpart, C; Butt, D). The distribution represents the sample divided into Lower (L) and Upper (U) levels, the type of blank (Slab, Flake and Unknown, blank dot) and type of raw material (Millstone and Flint red squares). Graphic A, distribution of Corticality between strata a and c and the type of blank identified; Graphic B, Removal series combinations in strata a and c and blank type; Graphic C, Cluster analysis and distances between the groups represented in PCA.

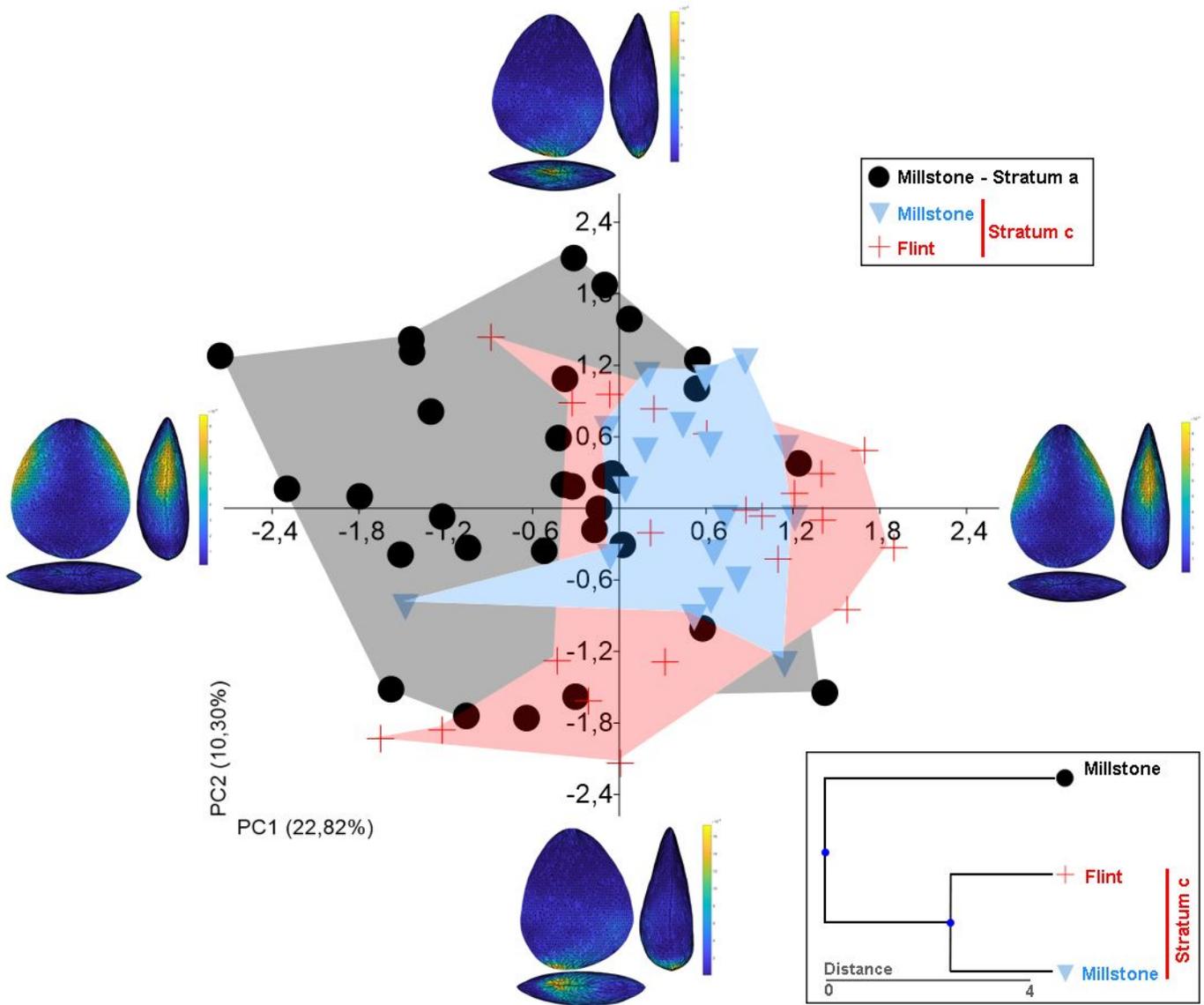


Figure 6

Principal component scatter plots of handaxes from La Noira, by strata and raw materials: millstone stratum a (black dots), millstone stratum c (blue triangles) and flint stratum c (red crosses). The geometric morphometric analysis was applied to 3D models, consisting of 5,000 semi-landmarks. It also includes convex hulls on each group to facilitate scatter plot visualization, and the warps' tool, representing morphology. Colour coding represents the most variable landmarks in shape trend described on positive and negatives scores of PC1 and PC2. Lower right-hand side; Cluster analysis and distances between the groups represented in PCA.

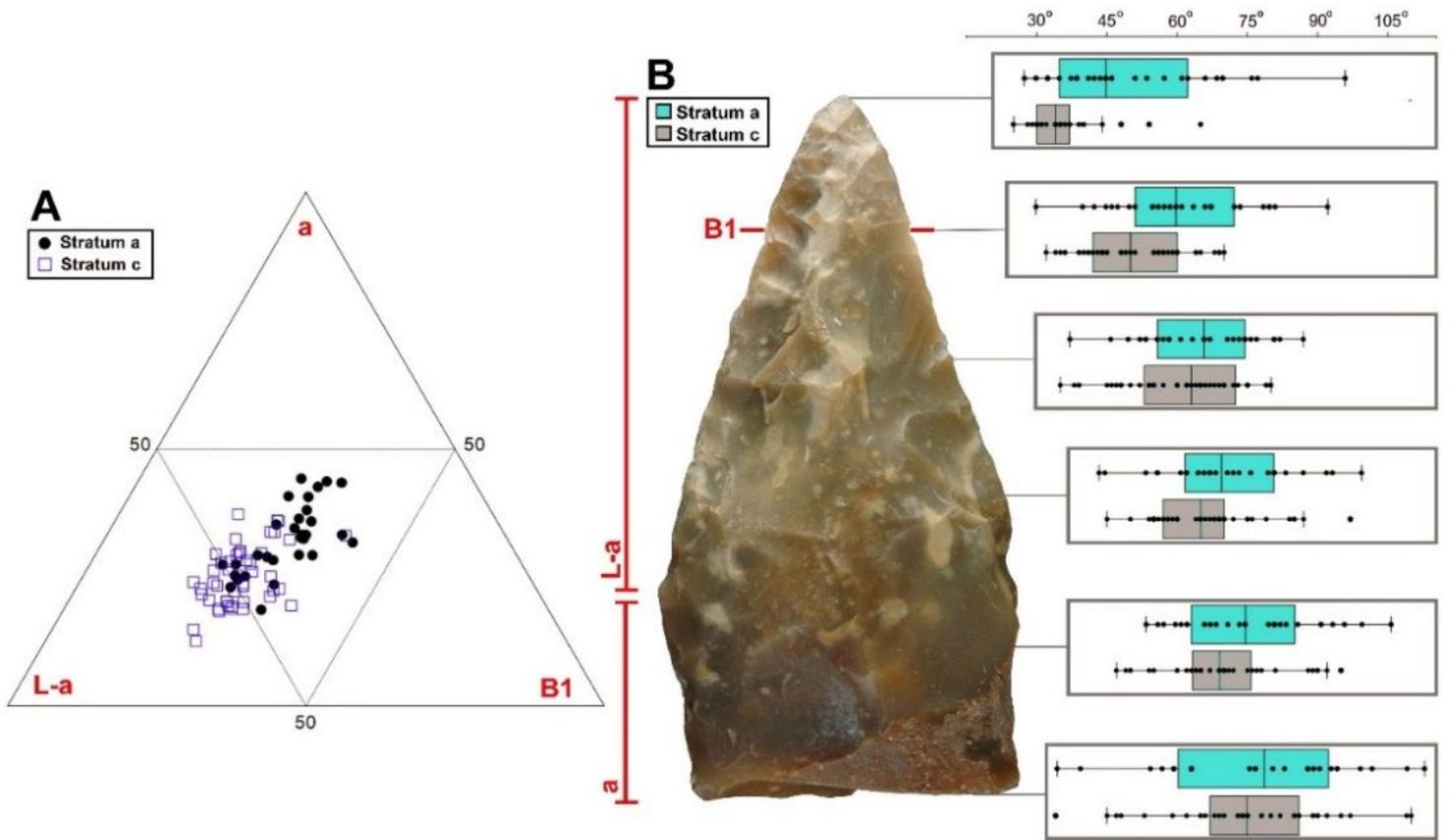


Figure 7

A) Ternary plot between Base Length (a), Distal Length ($L-a$) and Distal width ($B1$), from strata a and c. B) Angle distribution along the edges of tools from stratum a and stratum c of la Noira.

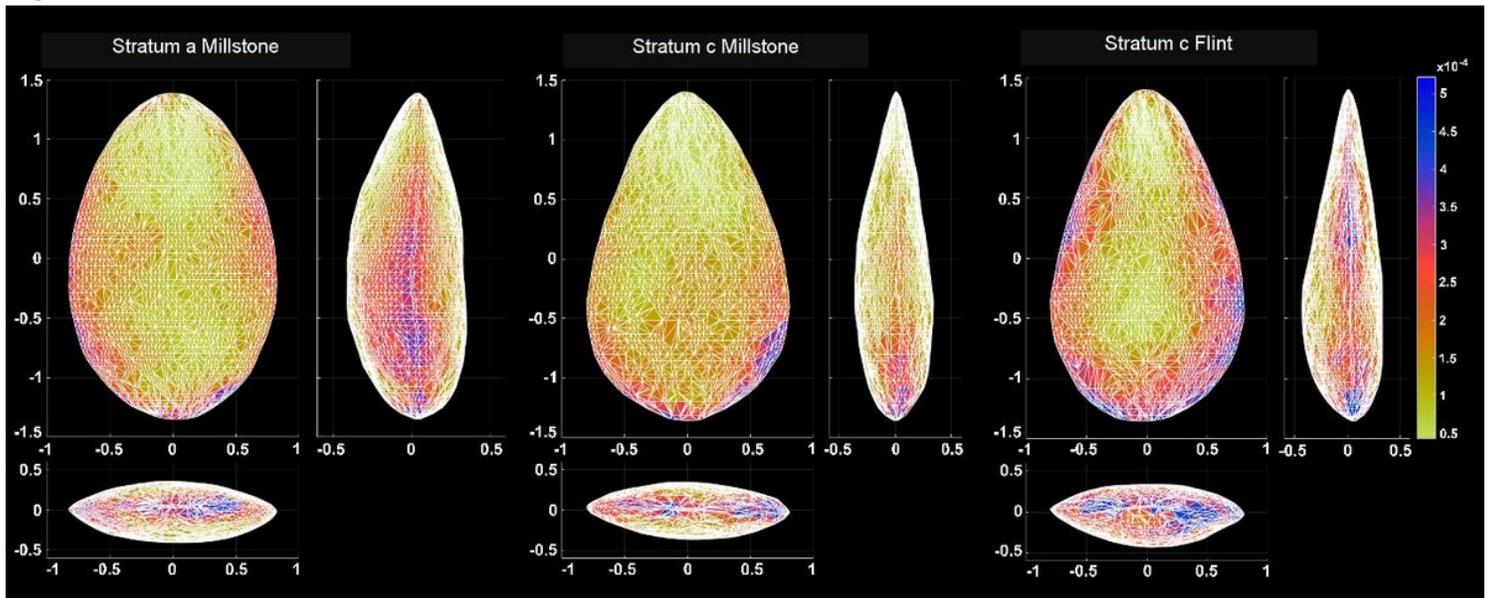


Figure 8

Mean shapes of LCTs from la Noira, stratum a and stratum c and the different raw materials (millstone and flint). Colour-coding represents the relative degree of variability of each individual semi-landmark reflecting the spatial distribution of variability in tools.

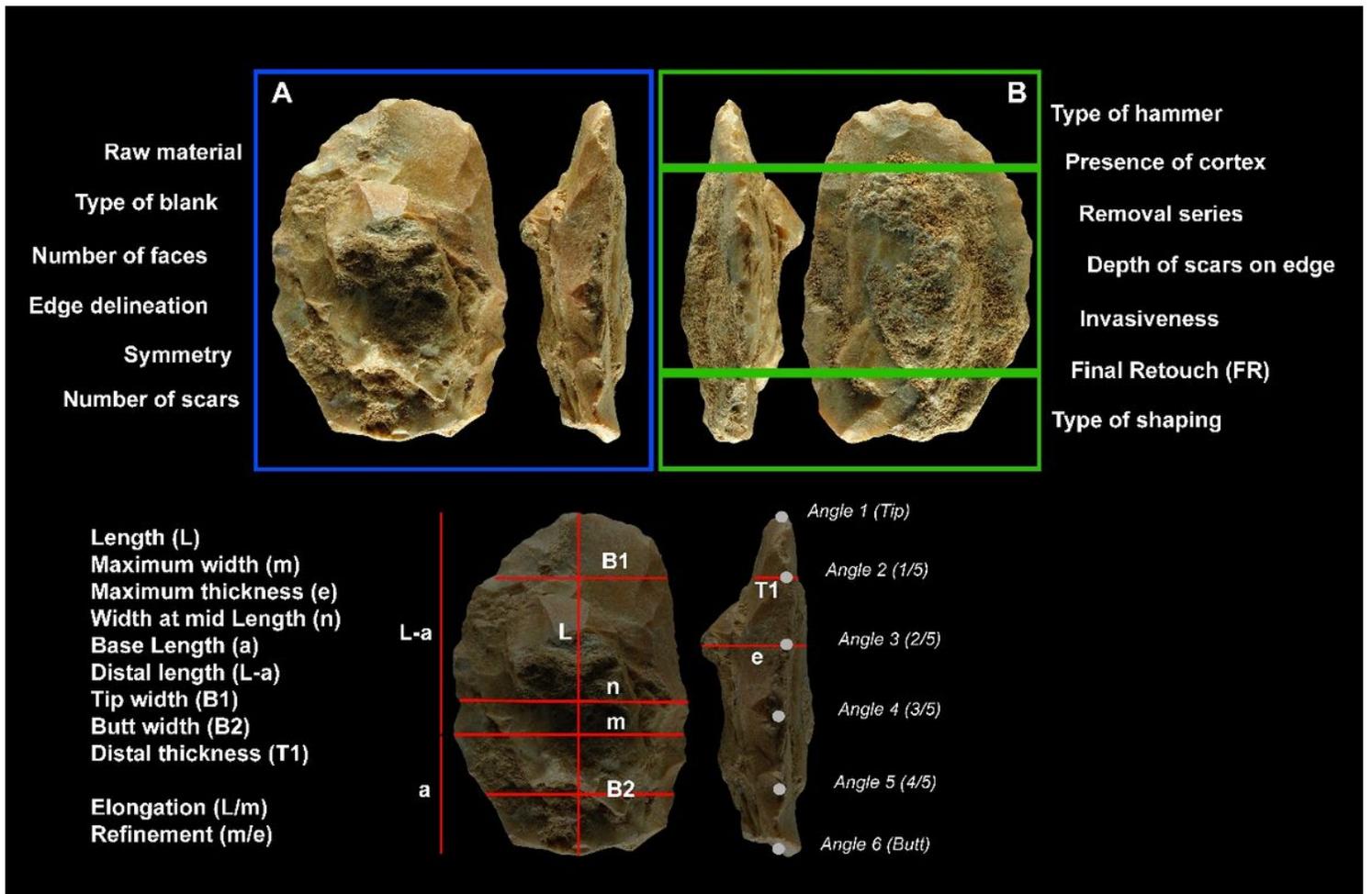


Figure 9

Technological analysis: technological features on each tool (A: considering each tool as one unit, and B: each tool divided into three parts), measurements, indices and angles (García-Medrano et al., 2020).

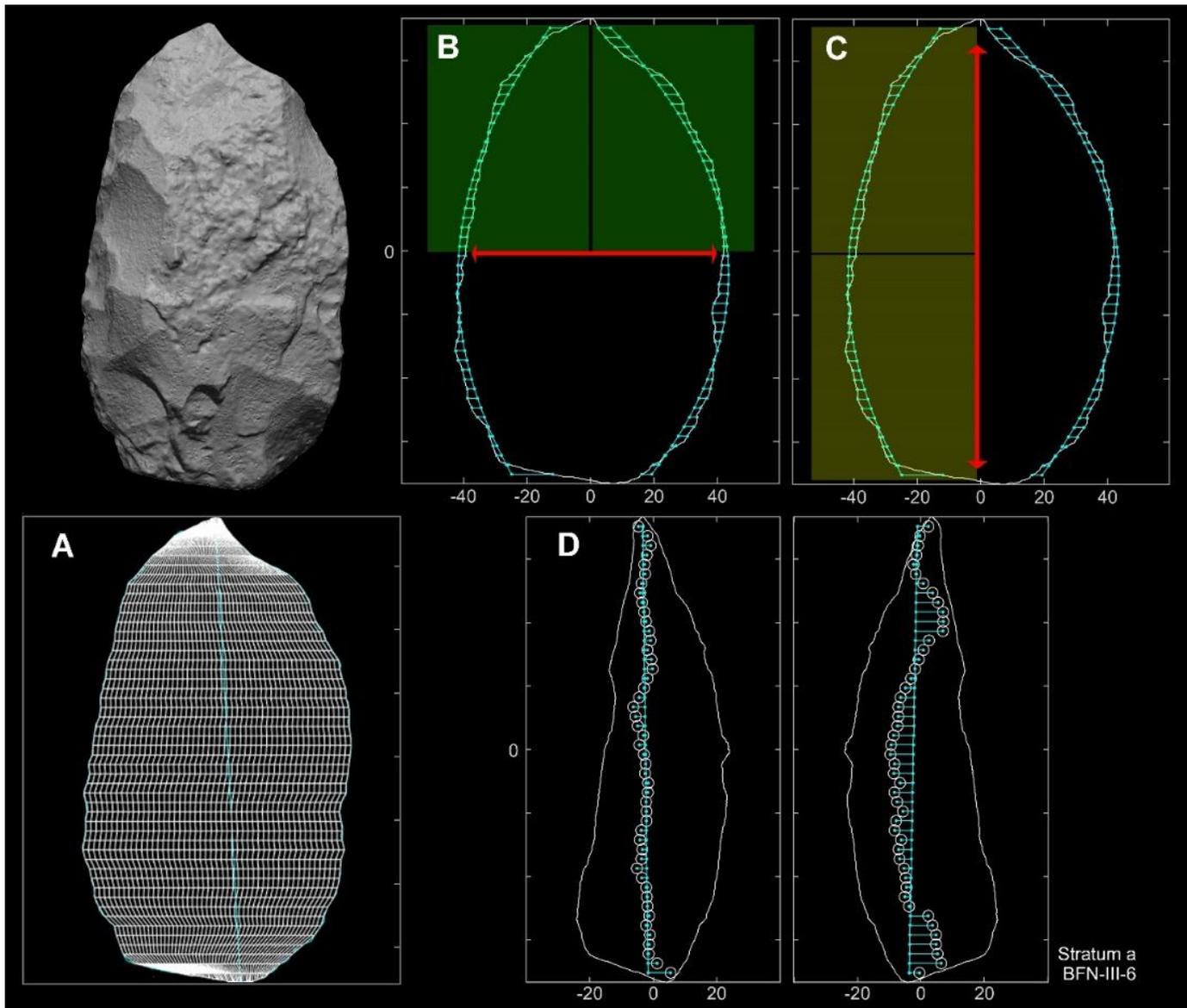


Figure 10

A) 5,000 points defining outlines and tool surfaces; B) Edge curvature: visualization of deviation from perfect bilateral symmetry (in green), and from perfect bifacial symmetry (in yellow). C) Edge irregularity.

Supplementary Files

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