Imposed form in the Early Acheulean? Evidence from Gona, Afar, Ethiopia

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Abstract

The appearance of ‘Large Cutting Tools’ in the early Acheulean is widely regarded as the first evidence for the imposition of intended forms on artifacts, with major implications for hominin cognitive and cultural capacities. However, the nature and extent of explicit design documented by these forms remains open to debate. To address this issue, we analyzed the complete collection of early Acheulean (ca. 1.7–1.2 Ma) flaked pieces from four sites (BSN17, DAN5, OGS12, and OGS5) in the Gona Project Area and compared these with all of the flaked pieces from two published Oldowan (>2.5 Ma) sites at Gona. By comparing shape variation to measures of flaking intensity and coverage, we sought to identify technological patterns indicative of intent. Results provide little support for the presence of discrete tool types or imposed morphological norms in our sample. Instead, we observe systematic patterns of raw material selection and core surface modification aimed at the production and maintenance of useful cutting edges on relatively large supports (cobbles and large flake blanks). This is consistent with prior characterizations of Acheulean tool form as arising from functional and ergonomic design imperatives for large hand-held cutting tools. Although the generalizability of these results to other sites remains to be seen, we propose that distinctive early Acheulean artifact forms may represent secondary accommodations to the primary goal of increasing tool size to meet the novel demands (e.g., extended use-life, enhanced transportability, utility for heavy-duty cutting) of a more general shift in hominin behavioral ecology at this time. Our results thus provide support for the presence of Acheulean design, not as the concrete realization of a ‘holographic model’ in the mind of the maker, but rather in the broader sense of deliberate technological choices made in view of behavioral goals and material constraints.

Keywords: Lithic technology; Early Stone Age; Handaxe; Large Cutting Tool; Pick; Shaping

Contents

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1 Introduction

The imposition of intended form on artifacts has long been viewed as a watershed in human cognitive and cultural evolution and is most commonly associated with the emergence of "Large Cutting Tools" [LCTs; cf. Long Core Tools; Shea (2013)] in the Early Acheulean (Holloway, 1969; Isaac, 1976; Kuhn, 2021). However, this interpretation of Acheulean LCTs as intentionally designed artifacts remains controversial. Alternative proposals range from the possibility that LCTs were unintended by-products of flake production (Noble and Davidson, 1996; Moore and Perston, 2016) to the suggestion that their form was “at least partly under genetic control” (Corbey et al., 2016: 6). Even accepting that LCT form was to some extent intended, there is substantial disagreement over the specificity of design. Some analyses have indicated that shape variation in Acheulean handaxes is largely a result of function-driven resharpening (McPherron, 2000; Iovita and McPherron, 2011) whereas others find it more likely to reflect normative expectations of what handaxes should look like (Shipton and Clarkson, 2015a; García-Medrano et al., 2019; Shipton and White, 2020). Such debates about the shape of Acheulean LCTs may appear narrowly technical but have broad relevance for evolutionary questions, including the origins of human culture (Shipton and Clarkson, 2015a; Corbey et al., 2016; Tennie et al., 2017; Liu and Stout, 2023), language (Stout and Chaminade, 2012), teaching (Gärdenfors and Högberg, 2017), brain structure (Hecht et al., 2015), and cognition (Stout et al., 2015; Wynn and Coolidge, 2016). To examine these questions, we studied the complete collection of Early Acheulean (ca. 1.7–1.2 Ma) flaked pieces from four sites (BSN17, DAN5, OGS12, and OGS5) in the Gona Project Area and compared them with all of the flaked pieces from two published Oldowan (> 2.5 Ma) sites at Gona [OGS7 and EG10; Semaw (2000); Semaw et al. (2003); Stout et al. (2010)]. By comparing variation in overall artifact shape (or “Bauplan” (Lycett and Gowlett, 2008)) to measures of flaking intensity and coverage, we sought to identify technological patterns that might reveal intent. The possibilities we considered include: a) intentional shape standardization reflecting normative expectations of what handaxes should look like, b) regularities of overall form arising as by-products of the intentional pursuit of particular morpho-functional attributes, and c) the absence of any intentional form imposition as in the case of simple debitage.

1.1 Identifying design

There is a broad consensus that refined handaxes and cleavers known from some later Acheulean (<1.0 Ma) contexts resulted from procedurally elaborate, skill intensive and socially learned production strategies (Sharon, 2009; Stout et al., 2014; García-Medrano et al., 2019; Shipton, 2019; Caruana, 2020; Moore, 2020), although debate over the presence of explicit, culturally transmitted shape preferences not determined by function continues (Iovita and McPherron, 2011; Wynn and Gowlett, 2018; Moore, 2020; Shipton and White, 2020). However, archaeologists have also noted the presence of less heavily worked and morphologically standardized LCTs (e.g., handaxes, cleavers, picks) in earlier Acheulean contexts (Leakey, 1951; Kleindienst, 1962; Wynn, 1979; Gowlett, 1986; Clark, 1994; Ludwig and Harris, 1998; Stout, 2011; Presnyakova et al., 2018). Such forms are typical of Acheulean assemblages in Africa prior to 1.0 Ma (e.g., Kleindienst, 1962; Ludwig and Harris, 1998; Lepre et al., 2011; Beyene et al., 2013; Diez-Martín et al., 2015; Presnyakova et al., 2018; Semaw et al., 2018; Torre and Mora, 2018), but continue to occur with variable frequency in later time periods (McNabb and Cole, 2015) and may be especially prevalent in eastern Asian (Li et al., 2021). Although formal tool types are commonly used to describe such early Acheulean assemblages, many workers now see a continuum of morphological variation (Presnyakova et al., 2018; Duke et al., 2021; Kuhn, 2021) including the possibility that simple flake production remained an important (Shea, 2010) or even primary (Moore and Perston, 2016) purpose of reduction.

Classically, LCTs are differentiated from Mode 1 pebble cores on the basis of size (> 10 cm) and basic aspects of overall artifact shape including elongation and flattening (Isaac, 1977) and the creation of a point (Kleindienst, 1962) . The consistent production of large, flat, elongated, and pointed forms in the Acheulean is generally thought to reflect the pursuit of desired functional and ergonomic properties for hand-held cutting tools (Wynn and Gowlett, 2018). Within this broad frame, numerous studies have examined the variation in overall LCT shape captured by various combinations of length, breadth, and thickness measures in an attempt to disentangle cultural, functional, raw material, allometric, and resharpening influences (e.g., Roe, 1969; Crompton and Gowlett, 1993; McPherron, 2000). It has been demonstrated that unplanned flaking can sometimes produce cores that fall into the LCT shape range (Moore and Perston, 2016) and this is one possible explanation of the relatively small "protobifaces" that occur in low frequencies in Oldowan assemblages (Isaac and Isaac, 1997). However, the early Acheulean is also distinguished from the Oldowan by the production of larger artifacts necessitating the procurement and exploitation of larger raw material clasts. Although studies of handaxe variation often focus on shape rather than size, this size increase is an important aspect of artifact design with relevance to both production and function.

Production of larger tools was accomplished either through a novel process of detaching and working Large Flake Blanks (LFBs) from boulder cores or by selecting larger cobble and slab cores (Isaac, 1969; Semaw et al., 2018; Torre and Mora, 2018). Both approaches may involve similar flaking "strategies" (e.g., bifacial or multifacial exploitation) to those present in the Oldowan

(Duke et al., 2021) but require more forceful percussion to detach larger flakes. This increases the perceptual-motor difficulty of the task (Stout, 2002) and in many cases may have been accomplished using different percussive techniques and supports (Semaw et al., 2009). These new challenges would have increased raw material procurement (Shea, 2010) and learning (Pargeter et al., 2019) costs, as well as the risk of serious injury (Gala et al., 2023). These costs strongly imply intentional pursuit of offsetting functional benefits related to size increase. Such benefits likely included tool ergonomics and performance (Key and Lycett, 2017a, 2017b), as well as flake generation, resharpening, and reuse potential (Shea, 2010). Early Acheulean LCT production is thus widely seen as a part of shifting hominin behavioral ecological strategies including novel resources and mobility patterns(Hay, 1976; Rogers et al., 1994; Linares Matás and Yravedra, 2021). Importantly, such functional and ecological interpretation speaks primarily to motivation (goals), and need not imply a lack of hominin technological understanding and intention.

The degree of intentional design reflected in the overall shape of Early Acheulean LCTs is more difficult to determine. For example, LFB production using a simple "least effort" bifacial/discoidal strategy will tend to generate predominantly elongated (side or end struck) flakes (Toth, 1982; Leader et al., 2018) whether or not this is an intentional design target. Similarly, the difficulty of flaking relatively spherical cobbles (Toth, 1982) might bias initial clast selection and subsequent reduction toward flat and elongated shapes, even in the absence of normative shape targets. Nevertheless, it has been argued that the shape of Early Acheulean LFBs was predetermined using intentional core preparation techniques (Leader et al., 2018; Torre and Mora, 2018) and many researchers perceive efforts at intentional shaping in the organization of flake scars on Early Acheulean handaxes and picks (Lepre et al., 2011; Beyene et al., 2013; Diez-Martín et al., 2015; Presnyakova et al., 2018; Semaw et al., 2018; Torre and Mora, 2018).

To date, evidence of early Acheulean shaping has generally come from qualitative assessments by lithic analysts. We do not dispute these assessments, but note that they are subject to reasonable concerns about possible selectivity, bias and/or overinterpretation (e.g., Davidson, 2002; Moore and Perston, 2016). The attribution of overall artifact shape imposition would be more compelling if supported by multiple lines of qualitative and quantitative evidence [i.e., a consilience of inductions; Whewell (1837)]. This is particularly true as qualitative and quantitative approaches often have complementary strengths and weaknesses. Currently, however, quantitative methods bearing on this question are underdeveloped and evidence is mixed. A three-dimensional geometric morphometric (3DGM) study by Presnyakova et al. (2018) concluded that LCT shape variation in the Okote Member (ca. 1.4 Ma) at Koobi Fora was largely driven by reduction intensity rather than different knapping strategies. However, this study did not directly address the presence/absence of design targets constraining the observed range of variation. Shipton et al. (2019) found that there was a correlation between LCT symmetry and reduction intensity (scar density index) in the lightly worked cleavers from Olorgesailie CL1-1 and conclude that this, along with several examples of flake scar patterning, provides evidence of the intentional imposition of symmetry. However, they remain agnostic as to whether this was motivated by functional, aesthetic, or social goals, leaving open the possibility that overall symmetry was a byproduct of more localized morpho-functional objectives. The purpose of the current study is to add to these various lines of evidence by developing and applying novel quantitative methods for assessing the imposition of overall artifact form in the early Acheulean at Gona.

In later Acheulean contexts, reduction intensity effects are commonly equated with resharpening and seen as supporting an alternative "byproduct" explanation of artifact shape regularity, rather than intentional form imposition (McPherron, 2000). Across heavily worked and relatively standardized LCT assemblages (e.g., Shipton and White, 2020), a lack of association between morphology and reduction intensity has thus been used as an argument-by-elimination for the presence of imposed morphological norms or "mental templates" (Shipton and Clarkson, 2015a; García-Medrano et al., 2019; Shipton et al., 2023). However, in the less heavily worked and more heterogenous assemblages typical of the early Acheulean (Kuhn, 2021), reduction intensity is more plausibly interpreted as an indicator of the extent of primary reduction rather than subsequent resharpening (Archer and Braun, 2010; Shipton et al., 2019). In this case associations between reduction intensity and shape would indicate intended effects of primary reduction, rather than byproducts of subsequent rounds of resharpening. For example, Beyene et al. (2013) found that increasing flake scar counts were associated with increasing handaxe refinement through time at Konso, Ethiopia, which may reflect a more general trend in the African Acheulean (Shipton, 2018). Disentangling such alternative explanations is a major challenge for quantitative approaches to the question of shape imposition.

Interpretive approaches address this quandary by "reading" the organization of scars on individual pieces to infer intent (Pelegrin, 2005), but an adequate method to objectively quantify these insights has yet to be developed. Lin et al. (2024) recently developed a method for quantifying flake scar orientations patterns, however this method still requires reading the direction of individual scars and it is not yet clear how results might be related to the question of shape imposition. The WEAP method of Garcia-Medrano et al. (2020) similarly provides a useful framework for integrating qualitative/interpretive technological attributes with quantitative shape metrics but does not address the reliability of individual attributes. Current measures of reduction intensity, such as the scar density index [SDI; Clarkson (2013)], are designed to estimate total mass removed from a core and have been shown to be reasonably effective (Lombao et al., 2023). However, mass removal was not the objective of Paleolithic flaking. Indeed, knapping efficiency is usually conceived as generating an outcome while minimizing required mass removal and energy expenditure (Režek et al., 2018). This is true whether the desired outcome is a useful flake, a rejuvenated edge, or a particular core morphology. In simple flake production, mass removed is probably a good reflection of the completeness of exploitation ("exhaustion") of cores and may have implications for required skill (Toth, 1982; Pargeter et al., 2023), as well as raw material economy (Shick, 1987; Reeves et al., 2021). However, in core shaping and resharpening, mass removal would typically represent an energetic and raw material cost to be minimized and might even interfere with function (Key, 2019). Without further information, relationships between artifact shape and reduction intensity are thus open to conflicting interpretations as evidence of intentional design or its absence.

Li et al. (2015) proposed a Flaked Area Index (FAI) as an alternative to SDI as a measure of reduction intensity, arguing that its validity is supported by a moderate correlation ($r = 0.424$) with SDI. However, they also explain that "flaked area does not necessarily relate to the number of flake scars... a small number of large scars can produce a large area of scar coverage, and conversely, a large number of small scars can produce a small area of scar coverage." (Li et al., 2015: 6). We suggest that FAI actually captures the spatial extent of modifications to the surface of a core, rather than the volume of material removed. It is thus complementary to the measure of volume reduction provided by SDI and provides additional information to inform technological interpretations (**Fig.** 1). For example, a correlation between FAI and artifact form without any effect of SDI would suggest a focus on "least-effort" shape imposition through large and/or strategically placed flake removals. On the other hand, an association between SDI and core form with no effect of FAI would be consistent with reduction (shaping and/or resharpening) focusing on spatially restricted areas (e.g., non-invasive retouch) on the core. In both cases we would also expect a breakdown in the expected association between FAI and SDI. For simple debitage with no systematic morphological constraints we would expect a lack of any effect of FAI or SDI on core shape. Conversely, strong correlation of core shape with both FAI and SDI would indicate a highly "designed" form achieved through extensive surface modification and volumetric reduction. In the current study we employed these theoretical expectations to evaluate evidence of the presence and nature of intentional shaping in the early Acheulean of Gona.

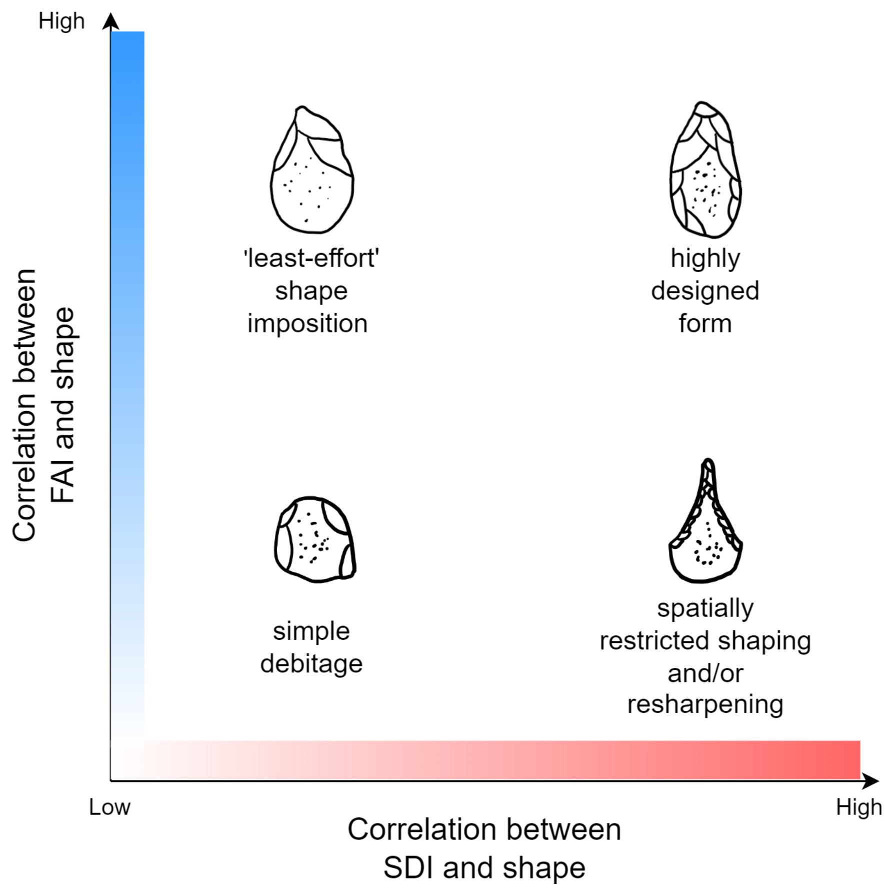

Figure 1: Technological interpretations of the relationship between artifact shape, flaked area, and scar density. Abbreviations: SDI: corrected scar density index; FAI: Flaked area index.

1.2 Measuring artifact form and modification

For our study, we are specifically concerned with the accurate description of morphological variation and estimation of artifact surface and flaked areas. Historically, debates over imposed form in the Acheulean have focused on basic aspects of overall artifact shape, such as elongation, flattening, and pointedness that are relatively easy to capture using sparse data. For example, McNabb (2022) recently concluded that the influential "Roe method" using 7 linear measurements is sufficient to "fairly represent the basic *bauplan* of LCTs." Typological groupings derived in this fashion have similarly been validated (Shipton and White, 2020) by analyses based on the much more detailed morphological information provided by three-dimensional geometric morphometric (3DGM) methods. Across 3DGM studies, the first two or three principle components (PCs) typically account for about 50% of variation and consistently correspond to basic features like elongation, relative thickness, pointedness, and position of maximum thickness that also emerge from lower resolution spatial data (Lycett et al., 2006; Archer and Braun, 2010; García-Medrano et al., 2019) and studies employing linear measures rather than spatial coordinates (Crompton and Gowlett, 1993; Pargeter et al., 2019). We are thus confident that the seven linear measures used in our study effectively capture relevant aspects of shape variation for our research question. To further confirm this, we compared shape PCs derived from our linear measures with the results of a 3DGM analysis of all scanned artifacts in our sample ($n = 31$; **Fig. 2**).

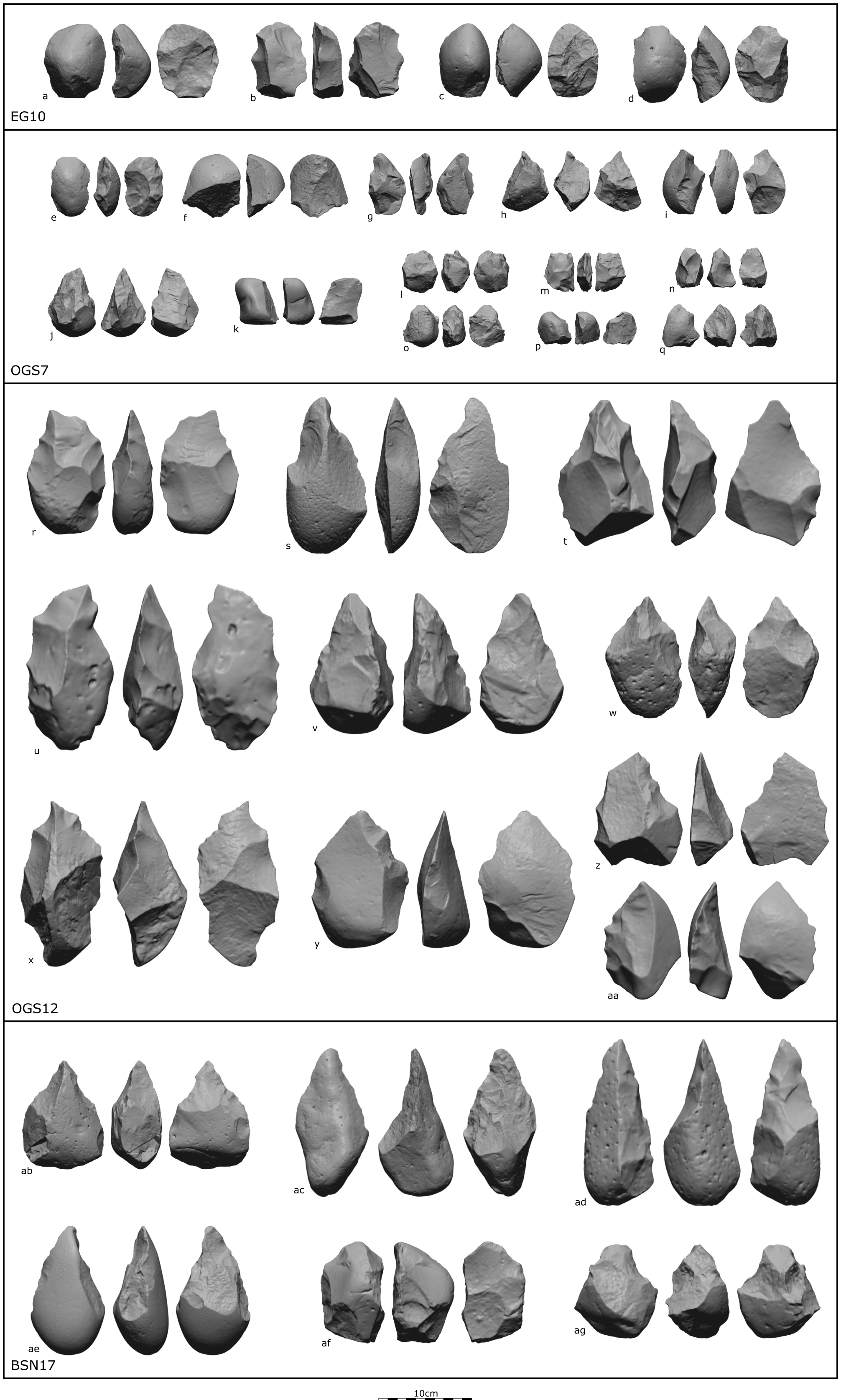

Figure 2: 3D Artifact scans from Gona used in this study.Artifact maximum dimension is vertical, and three views shown 90 degree rotation. The pieces, catalog number and typological classifications are: EG10: 1125 M1 FC (a), 1171 M1 FC (b), 1215 M1 FC(c), 1223 M1 FC (d). OGS7: 334 M1 FC (e), 335 M1 FC (f), 437 M1 FF (g), 485 M1 FC (h), 486 M1 FIB (i), 2016 "M1 FF "protopick" (j), 523 M1 FC (k), 2006 M1 FF (l), 2066 M1 FC (m), 2081 M1 FIB (n), 2092 M1 FC (o). OGS12: 16 M2 FC "handaxe" (p), 63 M2 FF "handaxe" (q), 226 M2 FF "handaxe" (r), 13 M2 FF "pick" (s), 74 M2 FC "pick" (t), 102 M2 FF "pick" (u), 2012 M2 FF "pick" (v), 115 M2 FF "knife" (w), 110 M2 FF "knife" (x), 113 M2 FF "knife" (y). BSN17: 35 M2 FC "handaxe" (z), 21 M2 FC "pick" (aa), 24 M2 FC "pick" (ab), 34 M2 FC "pick" (ac), 29 M2 FC "broken pick" (ad), 231 M1 FC "core" (ae) (M1: Mode 1, M2: Mode 2, FC: Flaked Cobble, FF: Flaked Flake, FIB: Flaked Indeterminate Base)

There is less evidence that conventional methods can accurately estimate artifact surface and flaked areas. Clarkson (2013) advocated the use of 3D surface area measures as more accurate than estimation from linear measures (e.g., surface area of a rectangular prism defined by artifact dimensions). However, he also found that the error introduced by the linear approach was a highly systematic, isometric overestimation of surface area and that results correlated with direct 3D measures with an impressive $r^2 = 0.944$ and no effect of variation in core shape. Insofar as it is variation in the relationship between surface area and flaking intensity that is of interest, rather than absolute artifact size, such systematic overestimation may not be problematic. Similar concerns apply to the estimation of flaked area. Traditionally, such estimates have been done "by eye" as a percentage of the total artifact surface (e.g., Dibble et al., 2005). Such estimations have been found to be reasonably accurate when compared to 3D methods, but with the potential for substantial error on individual artifacts (Lin et al., 2010). The accuracy of visual estimation has yet to be systematically studied in Early Stone Age cores like those from Gona. We addressed this question by comparing SDI and FAI estimates derived from linear measures and "by eye" estimation with the results of 3DGM analysis.

1.3 The Early Acheulean at Gona

Early Acheulean sites in the Gona Project area are distributed over a wide area within the Dana Aoule North (DAN), Ounda Gona South (OGS), and Busidima North (BSN) drainages in the Busidima Formation (Quade et al., 2004) and range in age from approximately 1.7–1.2 Ma (Semaw et al., 2018). The specific sites included in the current analysis are DAN-5, OGS-5, OGS-12 (all ca. 1.6–1.5 Ma), and BSN-17 (1.3 Ma), with ages estimated by stratigraphic position in the Gona sequence (Quade et al., 2008; Semaw et al., 2020). The Busidima Formation accumulated through fluvial deposition by the ancestral Awash River (Type I context) and its smaller tributary channels [Type II context; Quade et al. (2004); Quade et al. (2008)]. Oldowan sites at Gona all occur in Type I sediments, indicating channel bank/margin (OGS-7) or proximal floodplain (EG-10, EG-12) contexts close to the large, hetero-lithic clasts available from point bars in the axial river channel (Quade et al., 2004; Stout et al., 2005). Acheulean sites continue to occur in Type I contexts (BSN-17, DAN-5) but are also found in Type II sediments (OGS-5, OGS-12) reflecting increased utilization of large perennial tributaries to the ancestral Awash River (Quade et al., 2008). Clasts locally available in these tributaries were relatively small, implying that the large flakes and cobbles used to produce Acheulean artifacts were initially sourced from the axial river. A similar pattern of habitat diversification and increasing lithic transport distances has been described at other sites and may be typical of the early Acheulean (Hay, 1976; Rogers et al., 1994; Linares Matás and Yravedra, 2021). As with other early [i.e., > 1.0 mya; Stout (2011); Presnyakova et al. (2018)] Acheulean assemblages, the Gona collections include numerous "crudely made" handaxes and picks on large flake blanks and cobbles, as well as large (> 10 cm) unmodified flakes, flaked pieces interpreted typo-technologically as Mode 1 cores, and smaller debitage (Semaw et al., 2018; Semaw et al., 2020).

2 Materials and methods

2.1 Archaeological sample

Artifact collections analyzed here include in situ pieces excavated from intact stratigraphic contexts and surface pieces systematically collected from the sediments eroding from these layers. Surface pieces are included because the current technological analysis does not require more precise spatial association, stratigraphic, and chronological control. Our sample comprises the total collection of flaked pieces (Isaac and Isaac, 1997) from each site, regardless of size, as well as any large (> 10 cm) unmodified detached pieces (total $n = 226$). As summarized in Table 1, our analytic categories thus include Flaked Cobbles, Flaked Flakes, Flaked Pieces on Indeterminate bases, and Unmodified Large Flakes. Note that the Flaked Piece categories are not size dependent, and a number of small Flaked Flakes from Oldowan sites are thus included. Our intention is to avoid a priori assumptions about artifact typology, technology, or function. All artifact collections from Gona are housed at the National Museum of Ethiopia.

2.2 Artifact classification and comparison

Artifacts were classified according to initial form (pebble/cobble, detached piece, or indeterminate), presence/absence of flaking, technological interpretation ("Mode 1" vs. "Mode 2" FP), and archaeological context (Oldowan vs. early Acheulean sites). Mode 1 vs. Mode 2 classification of flaked pieces was based on qualitative assessment of LCT criteria reviewed in the Introduction (i.e. elongation, flattening, the creation of a point and, in the case of flakes, size). LCTs were additionally classified as handaxes, knives, or picks drawing on definitions from Kleindienst (1962) and Leakey (1971) as we understand them to be broadly employed in recent early Achuelean literature (e.g., Lepre et al., 2011; Beyene et al., 2013; Torre and Mora, 2018). In this scheme, handaxes include bifacially or unifacially flaked tools that are relatively flat and have a rough "teardrop" shape. Picks are thicker tools, often with trihedral or quadrangular sections and a clear point. Knives are lightly worked large flakes characterized by flaking mostly along one edge, often opposite the platform. The utility of classification to Mode and type was assessed through discriminant function analyses (DFAs) using artifact shape and reduction intensity variables. The aim of DFA analysis was to see if qualitative artifact types corresponded to analytically relevant patterning in our quantitative shape and reduction measures. Evidence for such patterning was on the basis of DFA classification success rates, visual assessment of clustering in DF plots, and using Hartigans' dip test for unimodality/multimodality of DF score distributions. Comparisons between artifact classes (initial form, presence of modification, Mode, typology) and contexts (Oldowan vs. Acheulean) with conducted using t-tests to assess significance and Cohen's d as a standardized measure of effect size.

2.3 Artifact measurement

Conventional linear measures capture the direction (e.g., length > width) but not the location of geometric relations (e.g., position of maximum breadth). We address this by collecting linear measures defined by homologous semi-landmarks. All artifacts were oriented along their maximum dimension, without respect to any other technological or morphological landmarks, which was measured and defined as "length" (L). The next largest dimension orthogonal to length was used to define the plane of "width," (W) with the dimension orthogonal to this plane defined as "thickness" (T). Additional width (W_1, W_2, W_3) and thickness (T_1, T_2, T_3) measures were then collected at 25%, 50%, and 75% of Length, with the piece oriented so that $W_1 > W_3$. To partition variation in shape from variation in size, we employed geometric mean size-adjustment (Lycett et al., 2006). For each artifact, we divided each linear measure (L, W_1, W_2, W_3, T_1, T_2, T_3) by the geometric mean for that artifact (the seventh root of the product of these seven measurements). Geometric mean (GM)-adjusted variables were then submitted to a principal components analysis (PCA; covariance matrix) to identify the main dimensions of shape variation.

To estimate surface area, we combined our measure of length (L) with maximum width (W_m)

and thickness (T_m) measures in a prism-based formula ($2LW_m + 2LT_m + 2\,W_mT_m$). Surface area calculated in this way correlates with mass$^{2/3}$ at $r = 0.966$ in our sample. Calculated surface area was then used to derive the Scar Density Index: SDI = number of flake scars > 1 cm per unit surface area (Clarkson, 2013; Shipton and Clarkson, 2015b). The length (maximum dimension) of each flake scar was also measured. The Flaked Area Index [FAI: flaked area/total surface area; Li et al. (2015)] was estimated directly "by eye" as a percentage (nearest 5%) of the total artifact surface.

To assess the adequacy of shape descriptions based on our linear measures, we directly compared these with shape as quantified by 3D methods on the 31 artifacts for which scans are available. GM-transformed linear measures from these 31 artifacts were submitted to a variance-covariance matrix PCA. Principal components (PCs) with an eigenvalue greater than the mean were retained for analysis and the results compared qualitatively (morphological interpretation of PCs) and quantitatively (correlation of artifact factor scores) to 3D results. Stepwise regression was used to assess the amount of variance accounted for in cases where multiple 3DGM-PCs were found to be correlated with a single linear PC. Accuracy of surface area and flaked area estimates was assessed by correlation with 3D results.

2.4 Three-dimensional methods

3DGM analysis was conducted using the AGMT3-D (Herzlinger and Grosman, 2018). Artifacts were automatically oriented according to the axis of least asymmetry, then manually oriented following the same orthogonal conventions described in section 2.3. Then, a grid of 200 homologous semi-landmarks were overlain on each artifact's surface. Generalized Procrustes and PCA were then undertaken to explore the shape variability of the sample. The surface area of each artifact was calculated using the Artifact3-D program (Grosman et al., 2022). Artifact3-D was also used to automatically identify the flake scar boundaries and compute each scar's surface area, using the scar analysis functions of Richardson et al. (2014). While flaked and unflaked areas were mostly easily identifiable on the 3D scans, scar counts and photographs taken during the original analysis were used to resolve any ambiguities in the presence or location of cortex, ventral surface, and scars. In cases where this automatic scar segmentation did not match the real scar boundaries, the Merge function of the program was used to manually join or separate the erroneous regions. These boundaries were used to calculate the total 3D surface area of each artefact, as well as its flaked and unflaked area.

3 Results

3.1 Measurement validation

A PCA on GM transformed linear measures of the 31 scanned artifacts identified two PCs accounting for 71.5% of the variance. Linear-PC1 (Eigenvalue = 0.161) explained 49.7% of the variance. Factor loadings (**Table** 2) for Linear-PC1 reflect artifact elongation (i.e., a negative correlation of length vs. distal width and thickness).

This closely parallels the length vs. width and thickness tradeoff captured by 3DGM-PC1 (**Fig.** 3) and is reflected in a tight correlation of artifact scores produced by the two PCs ($r = 0.890$, $p < 0.001$; **Fig.** 4a). A second factor (Linear-PC2, eigenvalue = 0.07) explained an additional 21.8% of variance. This factor was less strongly correlated with its 3DGM counterpart (3DGM-PC2; $r = -0.458, p = 0.010$) probably because the remainder of the shape variability explained by Linear-PC2 is captured distributed across the higher order 3DGM-PCs 3 through 5 (Supplemental Fig. 1).. These PCs describe localized variation in relative thickness (especially of the base, 3DGM-PC 3 & 5) and breath (especially toward the middle/tip, 3DGM-PC 4). Although these PCs partition variation on the right margin (3DGM-PC3) from the left (3DGM-PC 4 & 5), none appears straightforwardly related to artifact symmetry. These 3DGM descriptions are of course much more detailed than is possible with our 7 linear measures, but we consider them to be broadly summarized by linear-PC2, which describes variation ranging from broad tips and thin butts on one extreme to pointed tips and thick butts on the other. Together, 3DGM-PC2, 3DGM-PC3 ($r = -0.359$, $p = 0.047$), 3DGM-PC4 ($r = 0.381$, $p = 0.035$), and 3DGM-PC5 ($r = -0.584$, $p < 0.001$) all correlate with Linear-PC2, cumulatively capturing whether the items are broad and flat or thick and pointed. A stepwise regression ($r^2 = 0.824$, F(4,26) = 30.408, $p < 0.001$, Probability-of-F-to-enter $\leq$ 0.050; Probability-of-F-to-remove $\geq$ 0.100) with Linear-PC2 as the dependent variable retained all four of these 3DGM-PCs as significant predictors. Use of high-resolution, coordinate-based scan data thus generates PCs that identify more specific shape attributes, but the underlying morphological variability captured by the linear and 3D analyses remains similar. In fact, for questions like our about basic variation in overall artifact shape, simple linear descriptions may be easier to work with, summarize, and interpret.

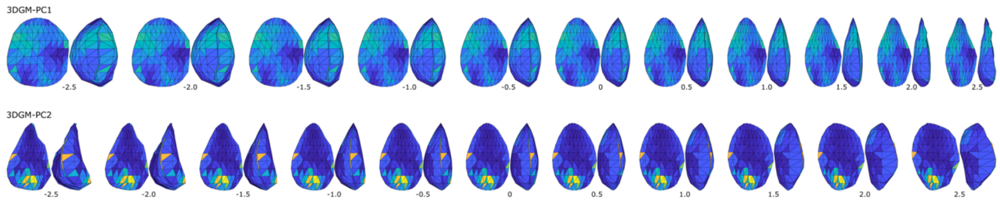

Figure 3: Principal Components 1 and 2 from the 3DGM analysis.

We thus concluded that linear measures are adequate to capture relevant shape variation and proceeded with a PCA on our full sample. This identified two PCs accounting for 79.7% of the variance. PC1 (Eigenvalue = 0.214) explained 55.9% of the variance. Factor loadings (**Table** 3) for PC1 reflect artifact flatness (i.e., an negative correlation of length and width vs. thickness), such that higher values indicate relatively thinner pieces. PC2 (Eigenvalue = 0.091) explained 23.8% of the variance. Factor loadings (**Table** 3) show that PC2 captures artifact pointedness (i.e., a negative correlation of tip width with length and butt thickness) such that higher values indicate shorter, less pointed forms.

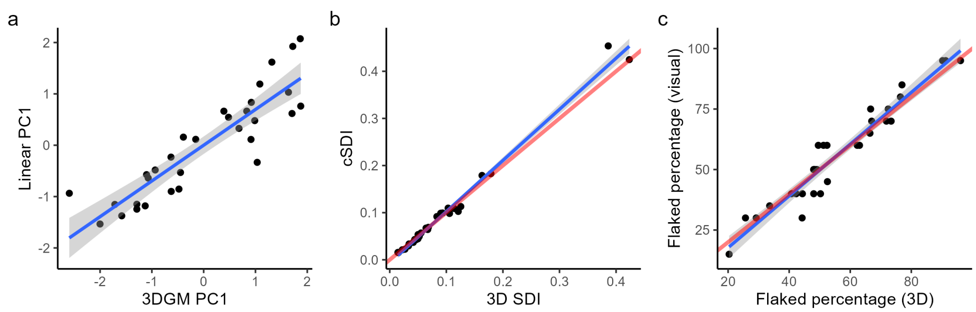

Figure 4: Comparison of 3D shape (A), scar density (B), and flaked area (C) measures with corresponding linear measurements and estimates. Abbreviations: PC = principal component; 3DGM = three-dimensional geometric morphometrics; SDI: corrected scar density index.

We also tested the validity of our two reduction measures, SDI and FAI. In agreement with Clarkson (2013), we found that surface area estimated from caliper measures displayed a strong correlation with ($r^2 = 0.982$, $p < 0.001$) but linear over-estimation of ($\beta = 0.452$) 3DGM surface area. This results in a systematic underestimation of SDI that scales with core size. However, a simple correction of the caliper estimate (multiplying by 0.5) eliminates surface area over-estimation and produces SDI values that agree with 3D values ($\$r2 = 0.988$, $p < 0.001$, $\beta = 0.910$; **Fig.** 4b). We thus proceeded to apply this correction to surface area estimates in the full sample. Insofar as these relationships are driven by basic geometry (roughly 2:1 ratio between the surface area of a rectangular prism vs. ellipsoid), we expect this correction to be generalizable to other Early

Stone Age (ESA) assemblages.

Visual estimation of flaked area approximated 3D measurement very closely ($r^2 = 0.929$; $p < 0.001$, $\beta = 0.868$; **Fig.** 4c) and without any systematic bias (paired t-test: mean difference = -0.24%, 95% CI = -2.35% to 1.86%, $p = 0.811$). Individual errors ranged between extremes of -10.46% and 14.24%. We thus considered visual estimation to be reliable in our sample.

3.2 Classification Validation

We first conducted a stepwise DFA on all flaked pieces ($n = 191$) with inferred technological Mode (one vs. two) as the grouping variable and shape PCs 1 and 2, corrected SDI (cSDI), and FAI as the independent variables. All variables were retained, yielding one canonical discriminant function DF (eigenvalue = 2.152, Wilks Lambda = 0.317, $p < 0.001$) which correctly classified 95.3% of artifacts. We thus concluded that Mode captures relevant patterning in our quantitative data and employed this distinction in subsequent analyses. There was no discernable difference in discriminant scores for Mode 1 flaked pieces from Oldowan ($n = 37$) vs. Acheulean ($n = 36$) contexts ($p = 0.703$). Mode 1 FPs from Oldowan contexts include 7 (19%) small, flaked flakes, three of which were misclassified by the DFA as Mode 2. When flaked flakes are excluded from the comparison, there are no significant differences in shape or DFA scores between Mode 1 flaked pieces from Oldowan vs. Acheulean contexts. Interestingly, however, Acheulean Mode 1 flaked cobbles are much larger (mean weight 481 g vs. 186 g, Cohen's d = 1.137, $p < 0.001$) and less heavily reduced (mean cSDI 0.06 vs. 0.10, Cohen's d = -0.949, $p < 0.001$) despite having similar FAI (mean 0.52 vs. 0.46, Cohen's d = 0.271, $p = 0.266$).

Next, we conducted a stepwise DFA on all flaked Mode 2 pieces (i.e., excluding unmodified large flakes, $n = 118$) with typology (handaxe, pick, knife) as the grouping variable and the same four independent variables. All four variables were again retained, producing two DFs (DF1: Eigenvalue = 1.02, 86.3% of variance; DF2: Eigenvalue = 0.240, 13.8% of variance; Wilks Lambda = 0.322; $p < 0.001$) which correctly classified 73.7% of artifacts. A plot of artifact DF values (**Fig.** 5a) shows substantial overlap between types, with handaxes occupying an intermediate position between picks and knives. As such an intermediate type, handaxes were correctly classified by only 53.7% of the time (Table 4). Visually, the DF1 distribution appears weakly bimodal with the handaxe centroid falling between two peaks, although the distribution is not actually significantly non-unimodal (Hartigans' dip test for unimodality/multimodality, D = 0.0433, $p = 0.2073$). Inspection of DF coefficients shows that DF1 captures a correlation between FAI and Linear-PC2 such that increasing FAI is associated with greater pointedness. The distribution of DF1 values thus reflects a distinction between pointed, heavily worked "picks" and less pointed, more lightly worked "knives." This, in turn largely corresponds to the different morphology of flaked cobbles vs. flaked flakes (**Fig.** 5b). We thus find no evidence that traditional Achuelean LCT types are a useful way to organize our data, and we abandon them in subsequent analyses, focusing instead on reduction Mode and initial blank form.

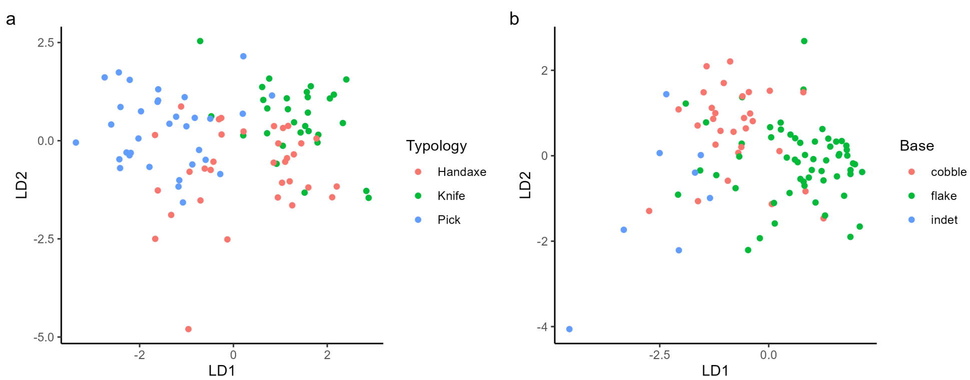

Figure 5: DFA results.

3.3 Effects of Reduction on Shape

To assess the influence of flake removals on Flaked Piece (FP) form, we examined the association between our reduction measures (cSDI and FAI) and FP shape (PC1, PC2). Summary statistics are presented in Table 5. In the complete sample of flaked pieces ($n = 191$), we observed weak but significant effects of cSDI ($r = -0.361$, $p < 0.001$) and FAI ($r = -0.294$, $p < 0.001$) on linear-PC1(flatness) and of FAI only on linear-PC2 (pointedness; $r = -0.443$, $p < 0.001$). However, these overall effects conflate different trends in Mode 1 vs. Mode 2 FPs, as well as in FPs executed on flake vs. pebble/cobble bases. Within categories, we observed no significant effects of cSDI whereas FAI had variable relationships with FP form.

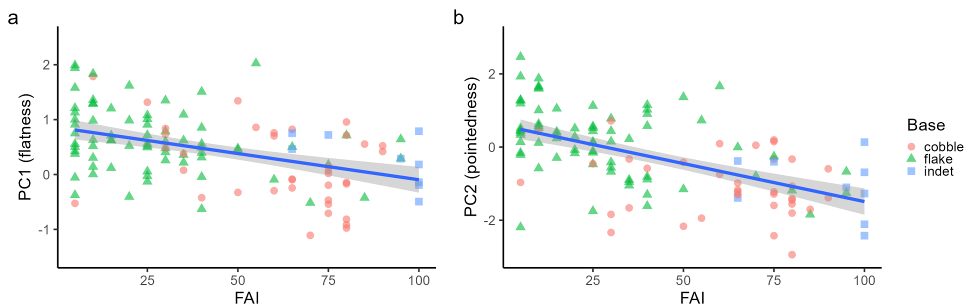

Figure 6: Effect of FAI on Mode 2 flaked piece shape across cobble, flake, and indeterminate bases. Abbreviations: PC = principal component; FAI: Flaked area index.

In Mode 1 FPs, a weak negative effect of FAI on PC2 ($n = 73$, $\beta = -0.007$, $r = 0.271$, $p = 0.020$) suggests that increasing extent of modification tends to slightly increase pointedness. No effects of FAI on PC1 or of cSDI on either PC approach significance. FAI and cSDI are moderate-to-weakly correlated ($\beta = 0.001$, $r = 0.446$, $p < 0.001$).

In Mode 2 FPs ($n = 118$), reduction measures have different effects depending on initial blank type. In the complete sample of Mode 2 FPs (**Fig.** 6), pieces range from broad and flat, lightly worked flake bases to rounder, more pointed, and more heavily worked cobble bases. However, effects of reduction within base categories are less consistent.

Mode 2 flaked cobbles ($n = 37$) display a weak negative effect of FAI on PC1(flatness; $\beta = -0.011$, $r = 0.368$, $p = 0.025$), no effect of FAI on PC2(pointedness), and no association between FAI and cSDI ($r = 0.114$, $p = 0.502$), thus showing minimal evidence of shaping. Flaked flakes (n = 72) show negative effects of FAI on PC1 ($\beta = -0.008$, $r = 0.289$, $p = 0.014$) and, more strongly, PC2 ($\beta = -0.018$, $r = 0.425$, $p < 0.001$) as well as a moderate correlation between FAI and cSDI ($r = 0.570$, $p < 0.001$). Thus, increasing flaked area is associated with increasingly thicker and more pointed forms and there is a tendency for additional flake scars to increase flaked area. Comparison of Mode 2 flaked flakes with unmodified large flakes from Acheulean contexts ($n = 35$) shows that ranges of shape variation substantially overlap but that flaking generally reduces both PC1 and PC2. In fact, regressions of PC1 and PC2 on FAI show y-intercepts that closely approximate unmodified flake mean values (0.839 vs. 0.780 and 0.679 vs. 0.591, respectively) and significantly negative slopes as FAI increases (**Fig.** 7).

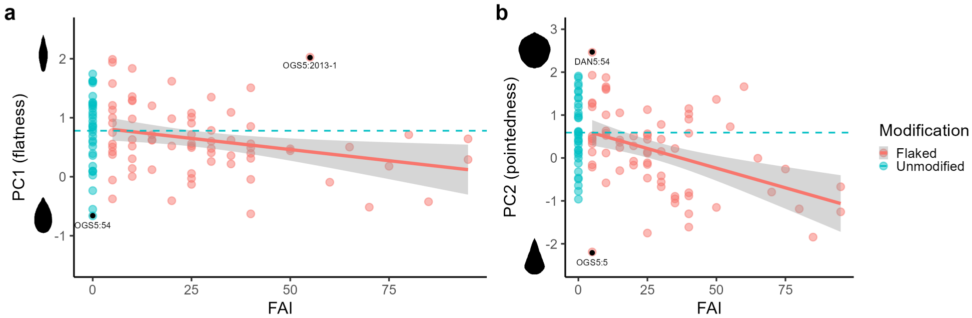

Figure 7: Effect of FAI on large flake shape. Silhouettes depict the GM-transformed Thickness (A) and Breadth (B) values of the extreme cases labeled in the plots. Abbreviations: PC = principal component; FAI: Flaked area index.

A small number of Mode 2 FPs ($n = 9$) were so heavily modified (mean FAI = 89%, range 65-100) that the blank form could not be determined. These heavily worked "indeterminate" cores tend to show similar PC1 (flatness) and PC2 (pointedness) values to cobble-base cores (i.e., thicker and more pointed than flake cores) and to follow general trends of shape change with increasing FAI observed across base types (**Fig.** 6).

3.4 Cobble selection

Although there is little evidence of intentional shaping of cobbles at Gona, it is also clear that Mode 2 flaked cobbles are more elongated than Mode 1 flaked cobbles and represent an extreme with the range of cobble shapes and sizes found in Type 1 channels in the Busidima Formation (Quade et al., 2004). This is not simply an analytical artifact of classifying elongated flaked cobbles as "Mode 2" while selectively omitting rounded forms: the complete sample of large (≥ 750 g) cores in our sample ($n = 25$) is dominated by relatively elongated forms (median L/W = 1.66). The small number ($n = 5$) of large, rounded (L/W < 1.33) cores in the sample are also anomalous in being very lightly worked compared to more elongated large FPs (mean scar count = 4.2 vs. 10.45, $p < 0.001$; mean cSDI = 0.013 vs. 0.029, $p < 0.001$; mean FAI = 36 vs. 65, $p = 0.016$). Thus, there is strong evidence for the intentional selection of large, elongated cobbles at Gona early Acheulean sites.

4 Discussion

Our analyses of flaked pieces from Oldowan and early Acheulean contexts at Gona support the presence of two distinct reduction Modes (1 and 2) that can be reliably discriminated using measures of artifact shape, flaking intensity, and extent of surface modification. However, they fail to justify further sub-division between conventional Mode 2 tool types (handaxe, pick, knife). Rather shape and reduction variation in our sample seems more closely related to initial blank form (flake vs. cobble). These results are consistent with the view (Presnyakova et al., 2018; Duke et al., 2021; Kuhn, 2021) that typological labels arbitrarily partition a continuum of artifact variation, although it remains to be seen if other variables (e.g. location of flake removals) would reveal more discrete clustering. For current purposes, we focused on analysis by flaking Mode and initial form.

Following criteria proposed in the Introduction, we find strong evidence of imposed form in the large flaked flakes from Acheulean contexts at Gona, weak evidence of shaping in Mode 2 flaked cobbles from Acheulean contexts, and little to no evidence of shaping in Mode 1 cores from both Acheulean and Oldowan contexts. Our framing of this research question and its proposed test criteria follows the preponderance of archaeological literature in conceptualizing artifact design as a binary presence/absence of intentionally imposed form (Dibble et al., 2017). However, we will now argue that our results are better interpreted as reflecting variation in the degree and nature of design expressed by ESA toolmakers. This shift in perspective recognizes that the purposeful production of desired morphological and functional features can be achieved by different combinations of raw material selection, blank production, and flaking strategies, including the preservation of function through patterned changes in morphology (Kuhn, 2021).

4.1 Large Flakes

As we argued in the Introduction, the systematic production of large flakes indicates attention to artifact size as a desired design feature. Many of these flakes would have possessed substantial lengths of sharp edge and could have been immediately useful as cutting tools without further modification. In fact, 33% of the large flakes in our total sample are unmodified. Notably, this is also true of the sub-sample from sites (OGS-5 and OGS-12) located in Type II, “tributary” sediments (29 of 82 unmodified, 35%). This likely reflects transport and discard of unmodified flakes from production sites closer to the axial river system sources of large clasts, consistent with the idea that such flakes were themselves treated as useful tools. We consider the alternative possibility, that unmodified flakes were unintended byproducts of local LCT production from transported boulder cores, to be less likely considering the energetic inefficiency of this strategy, as well as the absence of large boulder cores in the assemblages (but see discussion of LCTs on cobbles below).

Whether or not unmodified flakes were themselves desired "end products", a majority of large flakes in the sample were flaked to some extent. Our analyses indicate that this flaking was performed in a manner that produced systematic and directional shape changes. Specifically, increasing FAI is associated with progressive reduction in relative breadth (i.e., increasing relative thickness and elongation; PC1) and increasing pointedness (PC2). In contrast, variation in cSDI is not associated with artifact shape. These effects of surface modification extent but not reduction intensity indicate that it is the size and non-overlapping placement of flake removals that drives directional shape change, rather than the removal of mass in general. The observed correlation of cSDI with FAI further indicates that each new scar tends to remove additional unflaked area, consistent with the observed pattern of small numbers of relatively large and spatially distributed flake removals. This clearly differs from classic re-sharpening models, which emphasize shape change with decreasing artifact size as a byproduct of concentrated and repeated mass removal from particular areas of the artifact, such a working edges (Dibble, 1987; McPherron, 2003). It also clearly differs from the expected effects of un-patterned debitage on flake blanks, which does tend to increase relative thickness but also decreases elongation and is not associated with pointedness (Moore and Perston, 2016).

It is possible that the observed pattern reflects the intentional pursuit of an explicit morphological target or "mental template." This is generally seen as a strong claim implying rich mental representation and manipulation of spatial features (Wynn, 2002), cultural mechanisms for the intersubjective sharing of ideas of "appropriate" form (Wynn, 1995), and social reproduction of the skills required to reliably achieve these forms (Liu et al., 2023). A more cognitively and culturally "lean" alternative is that the pattern reflects a procedural and/or functional preference to establish (or rejuvenate) cutting edges at one end of the long axis. In the absence of effective thinning and volume management techniques, such a preference would naturally lead to narrowing/thickening of the piece overall and especially at the "tip," as is seen in our sample.

This preference might itself be a socially learned convention or "habit" (sensu Isaac, 1986), but it could also emerge from individual assessments of the technological affordances of large flake blanks. Such flakes are typically elongated and thus present: 1) two longer edges along the maximum dimension that are a natural focus for edge imposition, and 2) an ergonomic polarity defined by a thick (platform and percussion bulb) "butt" vs. a feather terminated "tip" (cf. Key et al., 2016; Wynn and Gowlett, 2018). Even on this minimal interpretation, however, we would argue that LFB flaking strategies at Gona present evidence of design in the sense of being intended to produce and/or maintain desired functional features of the LCT. This contrasts with patterns observed in cores classified as Mode 1 in our analyses which, as expected, appear to reflect simple debitage without intended morphological targets.

4.2 Mode 1 Cores

A Discriminant Function Analysis strongly supported the presence of two distinct morphological types in our sample (based on overall shape and flake scar characteristics), which we had previously typo-technologically interpreted as reflecting Mode 1 (débitage) and 2 (façonnage) flaking strategies. Consistent with this interpretation, flaked pieces assigned to Mode 1 showed little or no evidence of shaping . One potential exception is an unexpected tendency of increasing FAI to be associated with increasing pointedness. However, this effect is an order of magnitude weaker than that seen in large Acheulean flaked flakes and may be an artifact of our orienting protocol, which aligns cores such that width at 25% length is always less than width at 75% length. If reduction tends to increase asymmetry from initially rounded cobble forms, this could account for the weak convergence effect we observe.

The presence ($n = 14$) of relatively large (> 100 mm) Mode 1 flaked cobbles at Gona Acheulean sites raises the further possibility that at least some of these might be depleted cores from LFB production. However, none display scars > 90 mm (mean = 51.8 mm), most are very lightly reduced (mean = 5.7 scars), and none meet the 150 mm length cut-off used by Sharon (2009) to identify "large" cores suitable for LFB production. The largest Mode I flaked cobble in our sample is 137mm long, has five scars ranging from 25–85 mm long, and an FAI of 25%. We thus consider it unlikely that large Mode I flaked cobbles from Acheulean contexts were used for LFB production. The behavioral significance of relatively large, lightly-worked Mode 1 flaked pieces in Acheulean contexts is a question for future research.

4.3 Mode 2 Cores

Our most complicated results come from Mode 2 flaked cobbles. Evidence of intentional shaping is limited: FAI has a moderate effect on PC1 such that increasing flaked area produces relatively shorter, thicker, and narrower pieces. This violates expectations that intentional LCT shaping should increase elongation and pointedness. However, it also fails to align with a reported tendency for un-patterned debitage to decrease the thickness and increase the elongation of cobble cores (Moore and Perston, 2016). This may reflect the fact that Mode 2 flaked cobbles at Gona begin and remain relatively elongated (Table 4: mean L/W = 1.68) throughout reduction compared to starting ($n = 29$, mean L/W = 1.29) and ending (mean L/W = 1.34) cobble cores in the experiment of Moore and Perston (2016). The moderate trend toward thickening and shortening of flaked cobbles with increasing FAI might plausibly be an effect of particularly elongated initial cobble form. In the absence of intentional thinning techniques (Stout et al., 2014), flaking around the perimeter of an oblong cobble would be expected to preferentially reduce length and especially breath (due to the long axis providing more potential platforms, especially if knappers seek to maximize flake size) while preserving thickness. Along these lines, Toth (1985) reported that "roller" shaped cobbles tended to produce bifacial choppers in his unstructured debitage experiments.

Whether or not shaping occurred, it is clear that the elongated Mode 2 flaked cobbles at Gona do provide evidence of the selection of relatively large and elongated cobbles from within the range of rounded cobbles available from Type 1 channels in the Busidima Formation (Quade et al., 2004). This could reflect the intentional selection of large, elongated blanks suitable for LCT production, as has been proposed at other early Acheulean sites (Harmand, 2009; Texier, 2018; Duke et al., 2021). We would characterize such selection as a design choice even in the absence of subsequent shaping. However, large-cobble shape preferences might equally reflect preferences related to efficient LFB production. Geometrically, elongated cobbles afford greater potential maximum dimensions for detached flakes than do rounder cobbles of a similar mass. Flaking along the long axis of elongated cobbles enables the production of elongated, side-struck flakes (Torre and Mora, 2018) that are typical of the LFB Acheulean and which provide longer and more ergonomic (cf. Wynn and Gowlett, 2018) cutting edges than do round flakes. Flatter and more elongated cobbles are also generally easier to open and exploit (Toth, 1982; Whittaker, 1994; Texier, 2018). This is an increasingly important consideration as size increases due to the increased percussive force needed to detach larger flakes and the challenges of supporting and positioning larger cores (Semaw et al., 2009), particularly with cobbles that are large but not sufficiently massive to act as stationary targets for thrown hammerstones (Toth and Schick, 2019). We thus find it plausible that at least some typological picks, handaxes, and knives made on cobbles at Gona could have been by-products of large flake production rather than intended forms. Toth and Schick (Toth and Schick, 2019: 741) similarly note that "heavily reduced boulder cores can assume the form of smallish discoids and polyhedrons [and] may not be identified as sources of large flake blanks by many archaeologists". If this is true, such cores are distinguished from classic Mode 1 cores by allometric effects on raw material choice and flake placement rather than a shift to deliberate shaping.

The possibility that some Mode 2 flaked cobbles at Gona might be the remains of cores used for large flake production was initially suggested by informal, "experiential" knapping with Gona cobbles, during which attempts at LFB production produced pick-like forms as a byproduct. Consistent with this hypothesis, the mean (152.9mm) and median (156mm) length of Mode 2 cobble cores are both above the 150mm cut-off proposed by Sharon (2009) and the maximum scar length on each Mode 2 flaked cobble substantially overlaps with the size range of unmodified large flakes (Table 3). Importantly, this is also true of the largest flaked flakes at Gona, nine of which exhibit flake scars >100mm and thus could have been used as LFB cores. This possibility has also been suggested at Koobi Fora (Presnyakova et al., 2018) and might be relevant to understanding very large LCTs on flakes at other sites (e.g., Beyene et al., 2013).

Nevertheless, the fact remains that the preponderance of scars on large cobbles are from the removal of smaller flakes. Although these smaller scars could record preparatory flaking for LFB predetermination (Torre and Mora, 2018) and/or a subsequent stage of small flake debitage (Shea, 2010), it is difficult to rule out a role in shaping. Indeed, some pieces (e.g., Fig. 2 aa, ab, ac) exhibit delicate points and sharp edges that are strongly suggestive of intentional shaping. If these pieces did in fact begin as cores for LFB production, it is possible that they were subsequently shaped into cutting tools in their own right. Such lithic "upcycling" of depleted LFB cores would help to explain the transport of these pieces away from the axial river system. However, we should also be cautious not to overinterpret a small number of suggestive pieces pulled from a wider range of variation, as they may simply represent low frequency "spandrels" of un-structured debitage (Moore and Perston, 2016; Moore, 2020). These various possibilities remain to be tested, but we note that there is no a priori reason to think that Acheulean tool makers would have neglected potentially useful cores because they "belonged" to a particular reduction sequence or technological type.

4.4 *Implications for understanding the early Acheulean*

Early Acheulean technology is differentiated from the preceding Oldowan by changes in artifact size as well as morphology (Isaac, 1977). However, discussion of the technological, cognitive, and cultural implications of this transition has often focused on the emergence (or not) of intentional shape imposition (Holloway, 1969; Isaac, 1976; Gowlett, 1986; Wynn, 1995, 2002; Roche, 2005; e.g., Duke et al., 2021). Our results suggest that this emphasis may be misplaced, and that distinctive early Acheulean artifact forms might represent secondary accommodations to the primary goal of increasing tool size. From this perspective, early Acheulean shape imposition is best understood as reflecting an interaction between functional design goals and technological constraints (Wynn and Gowlett, 2018; Kuhn, 2021). Note that this would still imply intentional design choices. What is at issue is the nature of the goals being pursued and the strategies used to achieve them.

The consensus view is that Oldowan flaking goals focused on the production of sharp, cutting flakes through least effort debitage (Toth, 1985). Somewhat more controversially, Oldowan flaking may have included preferred debitage patterns (Stout et al., 2019) and/or intentional core maintenance and rejuvenation strategies (Delagnes and Roche, 2005). Our failure to find systematic effects of reduction on Oldowan flaked piece shape at Gona is consistent with this broad characterization. Starting from this Oldowan baseline, the production of larger cutting tools could in principle be achieved by increasing the size of cores and detached flakes and/or by attempting to produce and maintain cutting edges on cores themselves rather than on the smaller pieces detached from them. Both strategies are evident in the early Acheulean at Gona.

At Gona, large flakes appear to have been transported across the landscape and discarded either in their original form or after relatively light modification to impose desired cutting edges. This behavior combines the two size-maximizing strategies identified above by increasing flake size and then using these large, detached pieces as supports for flaked edges. On the other hand, the sample of large flaked cobbles at Gona displays shape variation more consistent with debitage than shaping. This leads us to suggest that some of these pieces might be depleted cores from large flake production (size-maximizing strategy 1) that have been "upcycled" as large core tools (size-maximizing strategy 2). In this way, the full range of artifact types and patterns of shape variation in the Gona early Acheulean can be parsimoniously accounted for as the expression of two strategies for increasing cutting tool size.

This interpretation has three main implications. First, it supports the view that the Acheulean initially emerged as a set of technological strategies for increasing cutting tool size, especially by striking large flakes (Isaac, 1969). Hypothetically, this size increase might have been favored by novel functional priorities of hominins for their tools, such as extended use-life, enhanced transportability, and utility for heavy-duty cutting (Shea, 2010; Toth and Schick, 2019). It may also have been motivated and/or enabled by increases in hominin body size. These overlapping possibilities appear likely to be mutually reinforcing rather than mutually exclusive. In fact, the appearance of the Acheulean between 1.95 Ma Gossa et al. (2024) and 1.7 Ma (Lepre et al., 2011; Beyene et al., 2013; Duke et al., 2021) is roughly contemporaneous with an increase in the number, size, and ecogeographic range of stone tool sites in general (Plummer, 2004), as well as evidence of habitat diversification and greater lithic transport distances for Acheulean sites specifically (Hay, 1976; Rogers et al., 1994; Quade et al., 2008; Torre et al., 2008), increasing emphasis on large animal butchery (Linares Matás and Yravedra, 2021), and increases in hominin brain and body size (Antón et al., 2014) including the first appearance of *Homo erectus* between 2.04–1.95 Ma (Herries et al., 2020). Increased cutting tool size is a plausible response and/or enabling factor to many of these shifts and is in that sense appears "overdetermined" by available evidence. Importantly, the current study does not resolve the extent to which the production and transport of early Acheulean tools around the landscape (Presnyakova et al., 2018) occurred through planned logistical (Binford, 1980) activities of individuals and/or collaborating groups vs. the cumulative effects of independent transport and recycling events over time (Reeves et al., 2023). Implications for planning and prospection capacities (Szpunar et al., 2014) thus remain unclear.

Second, it reinforces a growing consensus (Presnyakova et al., 2018; e.g., Duke et al., 2021; Kuhn, 2021) that early Acheulean LCT types artificially partition a continuum of variation rather than representing distinct target forms. More specifically, we propose that these forms emerge as the expression of a generic goal of cutting tool size maximization implemented across varying material constraints and opportunities. This is particularly relevant to the interpretation of "picks," which have long been viewed as a morphologically distinct but functionally mysterious tool type. Toth and Schick (2019) note that picks do not appear designed to provide good cutting edges but also do not show use-wear consistent with digging. This leads them to speculate that picks may have been specialized weapons used to dispatch large, wounded animals with a blow to the head. However, picks are a common, persistent, and morphologically variable artifact type in the early Acheulean, which argues against such a narrow function. We suggest that typological picks may lump together a variable mix of depleted LFB cores and large cutting tools made on relatively thick (cobble or flake) blanks, possibly including upcycled LFB cores. On this interpretation, picks would be part of a continuum of morphological variation produced by different raw material forms and complex reduction histories, rather than a distinct tool type designed for novel function. Due to such constraints, picks as a class may appear less well designed for cutting than LCTs produced on thinner blanks. However, the relationship between tool morphology and cutting efficiency is complex and multivariate (Key, 2016), and the relative utility of short and/or higher-angle edges on a more massive tool is not well understood across diverse cutting tasks.

Picks as an artifact class have not received the same attention as handaxes and cleavers and we are unaware of any broad comparative synthesis. Beyene et al. (2013) report that picks at Konso are relatively conservative in shape and scar counts over a period from 1.75–1.2 Ma during which associated handaxes show clear increases in refinement. They thus suggest that pick function may already have been effectively optimized by 1.75 to 1.6 Ma whereas the cutting function of handaxes continued to be enhanced. This is broadly consistent with the current suggestion that typological picks identify a morphological extreme produced by raw material features (especially thickness) that constrain or discourage the refinement that might be developed on other blanks. From 1.75–1.2 Ma, these ad hoc and/or less refined cutting tools appear to have remained a stable element in the Konso tool kit. However, they are nearly absent at 0.85 Ma, coincident with the appearance of "considerably refined" handaxes. Indeed, picks are not commonly reported to co-occur with refined handaxes in later Acheulean contexts anywhere. On a traditional functional interpretation, this would imply that whatever it is that picks were originally designed to do also became less important in these contexts. The alternative possibility suggested here is that increased investment in handaxe refinement decreased the perceived value of producing and using ad hoc core tools for similar functions.

Lastly, our interpretation suggests that LCT variation at Gona probably does not reflect intentional imposition of morphological norms (cf. Holloway, 1969) or detailed mental templates (Deetz, 1967). Instead, we would focus attention on the cognitive and cultural implications of size maximization strategies. As reviewed by Stout (2011), these stem from 1) the physical and strategic challenges of quarrying large flakes and 2) the increased complexity of knapping action hierarchies resulting from the addition of novel sub-goals (e.g., create a cutting edge) involved in shaping large flake and cobble cores into useful tools.

Systematic large flake production strategies and techniques are qualitatively different from small-flake debitage (Isaac, 1969; Toth and Schick, 2019) and thus add to the volume of technical knowledge and know-how that must be acquired by individuals. This is directly relevant for inferring learning demands and the possible role of social support in Acheulean skill reproduction (Pargeter et al., 2019). Stout (2002) provides a modern example of large flake production that illustrates the potential scope of such demands. Interestingly, much earlier large flake production has been reported at the 3.3 Ma site of Lomekwi 3 (Harmand et al., 2015) but is argued to be poorly controlled with minimal core reduction, numerous steps and hinges, and extensive platform battering. Although concerns have been raised regarding the dating and context of this site (Dominguez-Rodrigo and Alcalá, 2019; Archer et al., 2020), it may provide an interesting technological comparison to early Acheulean large flake production.

With respect to knapping action organization, the intentional placement of flake removals to generate desired core morphologies demonstrates a more complex goal structure than is required for simple, least-effort debitage. Such complexity has implications for assessing cognitive demands including relational integration, temporal abstraction, and goal abstraction (Stout, 2011). For this reason, our study was designed to address concerns that intentional shaping might not actually be characteristic of early Acheulean technology (e.g., Moore and Perston, 2016). We did find evidence for (at least) the imposition of cutting edges on LFBs and offer this as a foundation for "minimum necessary competence" (sensu Killin and Pain, 2021) cognitive interpretations. We remain agnostic as to whether similar knapping complexity was demonstrated in the preceding Oldowan but note that the rare and un-standardized (Gallotti, 2018) occurrence of debitage on flakes prior to 2.0 Ma does not provide evidence of intentional shaping. Stout (2011) argued that elaborated small flake debitage methods contemporary with the early Acheulean, such as single platform Karari scrapers (Isaac and Isaac, 1997) and hierarchical centripetal cores (Torre et al., 2003), document complex goal structures including the intentional modification of the core morphology to enable subsequent flake detachments. Others have seen evidence of such intentions in earlier bifacial (Duke et al., 2021) and unifacial (Delagnes and Roche, 2005) debitage strategies. However, all of these interpretations are based on qualitative assessments of flake scar pattering and/or refitting and remain open to critique from quantitative and experimentally-based approaches contending that similar knapping patterns can emerge without "top down" intentions (Toth, 1985; Moore and Perston, 2016; Moore, 2020).

However these debates are eventually resolved, we would stress that the earliest demonstration of a particular capacity is unlikely to represent its earliest presence. Logically, the minimum capacities required to support a novel behavior must be present before the behavioral innovation can occur (Stout and Hecht, 2023) and may predate it substantially. We would thus argue that technological innovation in the early Acheulean was more likely stimulated by changing behavioral and ecological strategies that placed a premium on cutting tool size, rather than by the sudden emergence of new cognitive capacities. In this context, it is important to note that the preponderance of cognitive and especially neuroarchaeological investigations of handaxe manufacture (Stout et al., 2008; Stout, 2011; Stout et al., 2015; Hecht et al., 2023) have studied refined, later Acheulean forms and should not be generalized to discussions regarding the emergence of the early Acheulean (cf. Duke et al., 2021). These neuroarchaeological studies were made possible by a robust understanding of the specific knapping behaviors being modeled (Stout and Hecht, 2023). Similar studies modeling early Acheulean technology are clearly needed and we hope that investigations like the current one can help to provide the necessary behavioral foundation.

4.5 Generalizability to other early Acheulean sites

It remains to be seen to what extent current results can be generalized to other early Acheulean sites. It is clear that LFB production as seen at Gona is typical (Isaac, 1969) of the African Acheulean from its first known appearances (Lepre et al., 2011; Beyene et al., 2013; Mussi et al., 2023). Similarly, the transport and discard of unmodified large flakes has also been reported at Peninj (Torre et al., 2008) and Koobi Fora (Presnyakova et al., 2018) and may be more widespread than has been specifically noted in publication. The general pattern of light, non-invasive flaking we observe also appears typical of early Acheulean sites (reviewed by Presnyakova et al., 2018). However, the effects of reduction on LCT shape have not been systematically tested across sites in ways comparable to the current analyses. This makes it difficult to determine if rare examples of "well shaped" early Acheulean LCTs (e.g., Diez-Martín et al., 2019) represent distinct technological behaviors or extreme points along a continuum of variation. Presnyakova et al. (2018) argue for the latter, supported by shape effects of reduction intensity identified using artifact size and edge angle as proxies. However, these authors do not consider SDI or FAI and their analyses excluded any flaked pieces without "clearly defined tips and bases," thus limiting comparability with current results.

The occurrence of numerous large flaked cobbles (typological LCTs on cobble bases) at Gona is atypical for East Africa and may reflect local raw materials availability. Kuman (2007) reports that river cobbles from the nearby Blaaubank gravels are the dominant blank form in Gauteng "Cradle of Humankind" early Acheulean collections, possibly due to the rarity of larger boulder-size clasts. Relatively high frequencies of LCTs on cobbles have also been reported from Gadeb in Ethiopia (Torre, 2011). However, the large cobble cores at these sites have not been systematically studied as a distinct technological component or potential source of LFBs. Substantial use of large slabs/blocks for LCT production has been reported at Kokiselei 4 (Harmand, 2009) and Olduvai Gorge (Torre and Mora, 2005) but again it is not clear whether these could also have been sources for LFBs during some part of their reduction sequence. Interestingly, Presnyakova et al. (2018: Fig. 8) illustrate a boulder core with refitting large flake from FxJj65 that appears to be comparable in size (~150 mm long), shape (L/W $\approx$ 1.5), and reduction intensity to some of the more lightly worked flaked cobbles at Gona, providing at least anecdotal support for our interpretations. In sum, however, systematic comparison across published early Acheulean sites is not currently possible due to differences in research questions, methods, and data reporting practices. Clearly much work is needed to enable such comparison, but we do find some encouragement in the current finding that conventional linear measures, simple scar counts, and visual flaked area estimations are sufficient to describe relevant variation in shape and reduction intensity/extent.

5 Conclusion

Characteristic early Acheulean artifact forms including large flaked flakes and core tools began to appear ca. 2.0-1.7 Ma as part of a pervasive ecological and behavioral shift encompassing changing diet, ranging patterns, and habitat usage; increasing site frequency, density, and ecogeographic distribution; and the first appearance of *H. erectus*. Although the cognitive and cultural significance of this new lithic industry is often framed in terms of the emergence of discrete tool types and/or intentionally imposed morphological norms, we find little evidence at Gona to support this. Instead, we observe systematic patterns of raw material selection and core surface modification organized around the production and maintenance of useful cutting edges on large(r) supports. Such larger cutting tools may have been prioritized in newly emerging hominin life ways due to their extended use-life, enhanced transportability, and/or suitability for heavy-duty cutting.

This interpretation is consistent with a characterization of early Acheulean tool forms as emerging from a set of "design imperatives" for large hand-held cutting tools (Gowlett, 2006; Wynn and Gowlett, 2018) , specifically including elongation and ergonomic positioning of cutting edges (Key et al., 2016; Key, 2016). Our results thus provide support for the presence of imposed form in the broad theoretical sense developed by Kuhn (2021): not as the realization of a "holographic model" in the mind of the maker, but rather as the outcome of intentional technological choices made in view of material constraints and affordances (Moore, 2020). To the extent that some, but not all (Muller et al., 2022), later Acheulean assemblages provide stronger evidence of normative form imposition (García-Medrano et al., 2019; Shipton and White, 2020; Liu et al., 2023) this underlines the heterogeneity of lithic technologies subsumed within the "Acheulean Industry" and argues for more context-specific approaches to evaluating behavioral, cognitive, and cultural implications.

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