Landscape perspectives on variability in the Acheulean behavioural system in sub-Saharan Africa: *A view from Koobi Fora and Elandsfontein*

Dissertation

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II. SUMMARY / ZUSAMMENFASSUNG

The emergence of the Acheulean in Africa (~1.7 Ma) is understood to mark a key adaptive shift in several dimensions of hominin behaviour and cognition. Relative to the preceding Oldowan, some archaeologists associate the onset of the Acheulean with the expansion of hominin foraging ranges involving increased mobility and tool transport distances, variability in strategies of stone raw material procurement and use and increased spatial and temporal depths of planning in the organization of stone tool production. Other scientists, however, view Acheulean hominins as being tied closely to water and/or raw-material sources, rarely planning technological activities in substantial spatial or temporal anticipation of future need. Very little quantitative archaeological data, however, have been published to support either of these models. This may be due to a host of factors including (1) the paucity of localities that are geologically suitable to investigate Acheulean landscape use and (2) the emphasis in Acheulean studies on the *qualitative* study of the origins and production patterns of bifacial large cutting tools (hereafter ‘LCTs’), the marker of the Acheulean techno-complex.

Here I develop a series of methods to (1) interrogate how Acheulean hominins organized and economized their technology on a landscape scale, and to (2) quantitatively assess how shifts in hominin cognition are manifested archaeologically. Few contexts exist that are conducive to such studies. Two of the more suitable sets of sites are (a) a set of spatially separated semi-contemporaneous early Acheulean (~1.4 Ma) sites in Koobi Fora, east Turkana, Kenya, consisting of the localities of FxJj65, FxJj63, FxJj37 and FxJj21, and, (b) a ~10 km^2 dune field with multiple late Acheulean localities known as Elandsfontein, West Coast, South Africa (~1 Ma-600 Ka).

The methodological outcomes of this work were (1) the formulation of a model to quantitatively discriminate shaping (*façonnage*) from non-shaping (*débitage*) Early Stone Age products and (2) a new 3D Geometric Morphometric approach to characterizing and quantifying the forms of early Acheulean LCTs. 3DGM provided a means of documenting Acheulean artefact shape variability to a level of detail that may not easily be visible to, or measurable by, lithic analysts using traditional descriptive and linear measurements. I was then able to evaluate variation in Acheulean tool shape and size, across the landscape, against a range of predictors.

I applied these approaches to the Koobi Fora and Elandsfontein sites. My focus here was to (i) study geographic patterns of landscape usage among early Acheulean sites, and to (ii) compare and contrast patterns of technological organization between the early and later Acheulean.

A multitude of quantitative and qualitative analyses demonstrated that archaeological sites at Koobi Fora and at Elandsfontein were ‘fragmented’. In other words, hominins structured their tool manufacture, use, and maintenance patterns systematically and spatially across the landscape. This finding suggests that fragmentation may be a ‘pan-African’ feature of Acheulean hominin behaviour, potentially conflicting with previous inferences that Acheulean hominins were tied to water and raw-material sources, and did not plan their activities beyond immediate expedient tool manufacture and use (Deacon & Deacon, 1999; Shipton et al., 2018). Both early and late Acheulean hominins used the landscape in flexible and systematic ways, at the geographic extremes of sub-Saharan Africa, implying a depth of planning in Acheulean hominins wherein technological activities were undertaken in substantial anticipation of future needs.

Die Entstehung des Acheuléen in Afrika (~1,7 Ma) wird als eine wichtige, multidimensionale adaptive Veränderung des Verhaltens und der Kognition der Hominini angesehen. Im Vergleich zum vorangegangenen Oldowan verknüpfen einige Archäologen den Beginn des Acheuléen mit der Erweiterung des homininen Repertoires für die Nahrungsbeschaffung, das erhöhte Mobilität sowie Werkzeugtransportwege, Variabilität der Strategien für Akquisition sowie Nutzung von lithischen Rohmaterialien und größere räumliche sowie zeitliche Planungstiefe die Organisation der Steinwerkzeugproduktion betreffend beinhaltet. Andere Wissenschaftler sind jedoch der Auffassung, dass die acheuléenzeitlichen Menschen eng an Wasser- und/oder Rohmaterialquellen gebunden waren und selten technologische Aktivitäten in beträchtlicher räumlicher oder zeitlicher Vorausschau auf den zukünftigen Bedarf planten. Sehr wenige quantitative archäologische Daten wurden allerdings veröffentlicht, um eines dieser beiden Modelle zu untermauern. Dies kann auf eine Vielzahl von Faktoren zurückgeführt werden, darunter (1) die geringe Anzahl von Fundplätzen, die geologisch geeignet sind, um die Landschaftsnutzung im Acheuléen zu untersuchen, und (2) die Schwerpunktsetzung in Studien über das Acheuléen auf die *qualitative* Untersuchung der Herkunft und der Herstellungsmuster von bifaziellen Großschneidewerkzeugen sogenannten *large cutting tools* (nachfolgend ‘LCTs’), dem Leitfossil des Acheuléen-Technokomplexes.

Hier erarbeite ich eine Reihe von Methoden, um (1) zu erforschen, wie die homininen Vertreter des Acheuléen ihre Technologie im landschaftlichen Rahmen organisierten und ökonomisch gestalteten, und um (2) quantitativ zu beurteilen, wie sich Veränderungen in der Kognition der Hominini archäologisch manifestieren. Es gibt nur wenige Kontexte, die für solche Studien in Frage kommen. Zwei der geeigneteren Fundstellengruppen sind (a) eine Reihe von räumlich getrennten, circa zeitgleichen frühen Acheuléen (~1,4 Ma) -Fundstellen in Koobi Fora, Ostturkana, Kenia, bestehend aus den Lokalitäten FxJj65, FxJj63, FxJj37 und FxJj21, und (b) ein ~10 km^2 Dünenfeld mit mehreren späten Acheuléen-Fundplätzen, bekannt als Elandsfontein, Westküste, Südafrika (~1 Ma-600 Ka).

Die methodischen Ergebnisse dieser Arbeit waren (1) die Erstellung eines Modells zur quantitativen Unterscheidung von Formgebungs- (*façonnage*) sowie Nicht-Formgebungs- (*débitage*) Produkten des Early Stone Age und (2) eine neue 3D Geometric Morphometric (3DGM) -Vorgehensweise zur Charakterisierung und

Quantifizierung der Formen von LCTs des frühen Acheuléen. 3DGM bot die Möglichkeit zur Dokumentation der acheuléenzeitlichen Artefaktformvariabilität bis auf einen Detaillierungsgrad hin, der für Steinartefaktanalytiker unter Verwendung traditioneller beschreibender und linearer Messungen möglicherweise nicht leicht erkennbar oder messbar ist. Ich konnte dann die Vielfalt an Form und Größe der Werkzeuge des Acheuléen über die Landschaft hinweg anhand einer Bandbreite von Prädiktoren bewerten.

Ich wandte diese Ansätze auf die Fundstellen Koobi Fora und Elandsfontein an. Mein Fokus lag hier auf (i) der Untersuchung geographischer Muster der Landschaftsnutzung unter frühen Acheuléen-Fundplätzen und (ii) dem Vergleich sowie der Gegenüberstellung von Mustern der technologischen Organisation zwischen dem frühen und späten Acheuléen.

Eine Vielzahl von quantitativen und qualitativen Analysen zeigte, dass die archäologischen Fundstellen in Koobi Fora und Elandsfontein ‘fragmentiert’ waren. Mit anderen Worten, Hominine strukturierten ihre Werkzeugherstellung, -nutzung und -instandhaltung systematisch und räumlich über die Landschaft hinweg. Dieses Ergebnis deutet darauf hin, dass die Fragmentierung ein ‘panafrikanisches’ Charakteristikum des menschlichen Verhaltens im Acheuléen sein könnte, was möglicherweise im Widerspruch zu früheren Schlussfolgerungen steht, dass acheuléenzeitliche Hominini an Wasser- sowie Rohmaterialquellen geknüpft waren und ihre Aktivitäten nicht über die unmittelbare zweckmäßige Werkzeugherstellung sowie -verwendung hinaus planten (Deacon & Deacon, 1999; Shipton et al., 2018). Sowohl frühe als auch späte acheuléenzeitliche Menschen nutzten die Landschaft an den geographischen Extrempunkten des subsaharischen Afrikas flexibel und systematisch, was eine hohe Planungstiefe bei den Hominini des Acheuléen impliziert, womit technologische Aktivitäten in erheblichem Maße auf zukünftige Bedürfnisse ausgerichtet waren.

III. LIST OF PUBLICATIONS

Accepted publications

(1) Presnyakova, D., Archer, W., Braun, D. R., and Flear, W. (2015) Documenting differences between Early Stone Age flake production systems: an experimental model and archaeological verification. *PLoS ONE: 10(6), 1-26.* (Appendix I)

(2) Presnyakova, D., Braun, D.R., Conard, N.J., Feibel, C., Harris, J.W.K., Pop, C.M., Schlager, S., Archer, W. (2018) Site fragmentation, hominin mobility and LCT variability reflected in the early Acheulean record of the Okote Member, at Koobi Fora, Kenya. Journal of Human Evolution. 125,159-180. (Appendix II)

(3) Archer, W. and Presnyakova, D. (2019) Practical considerations in the application of 3DGM to lithic artifacts: an example of orientation error on bifaces. In *3D Data Acquisition in Bioarchaeology, Forensic Anthropology and Archaeological Contexts.* (Appendix III)

IV. PERSONAL CONTRIBUTION

Description of the extent and significance of the personal contribution according to § 6,2 PromO of the University of Tübingen. Numbers follow the order in *III.LIST OF PUBLICATIONS*

(1) I was first and corresponding author, as well as the main person responsible for conceiving the study design, conducting the reported research, interpretation of data and writing the manuscript. The co-authors helped in the collection of data and discussion of the results (Will Archer and David R. Braun), writing of the manuscript (Will Archer, David R. Braun, and Wesley Flear).

(2) I was first and corresponding author, as well as the main person responsible for conceiving the study design, directing the excavations at sites FxJj65 and FxJj21, collecting the data, conducting the reported research, interpretation of data and writing the manuscript. The co-authors helped with the excavations (David R. Braun, Jack W.K. Harris, Will Archer), creating the experimental collection (Will Archer), helping to optimize the R code for landmarking the specimens (Will Archer), discussion of the results (Will Archer), creating a function in mesheR R package to transfer surface landmarks (unpublished package in R) (Stefan Schlager), developing an R function to measure edge angles on archaeological specimens (Cornel M. Pop), writing of the manuscript (Will Archer, Cornel M. Pop, David R. Braun, Nicholas J. Conard), and supervising the study (Nicholas J. Conard and Jack W.K. Harris).

(3) I was supporting co-author, helped to conceive the study design and provided editorial input to the manuscript.

CHAPTER 1. INTRODUCTION

1.1. Acheulean technologies and models of behavioural evolution in Africa

The ultimate questions in the field of human evolution are when, how and why we as a species evolved. One approach is to address these questions by focusing on modern human evolutionary history, entailing the study of fossil remains from anatomically modern humans (*Homo sapiens*) as well as the material culture associated with Middle and Later Stone Age occupations in Africa and the Upper Palaeolithic in Eurasia. Another approach, however, adopts a deeper perspective on hominin evolution, focusing rather on morphological and behavioural pivotal events that initiated with the divergence between great ape and hominin lineages as far back as 7-8 Ma (Langergraber et al., 2012). Evolution does not always take a gradual linear path from point A to B. Rather it is characterized by a multitude of branching speciation and extinction episodes, as well as adaptive losses and adaptive responses that independently evolved in the form of convergent trajectories.

What is clear today is that behaviours that set modern humans apart from the extant African apes emerged before 3 Ma in Africa. Dietary evidence suggests that hominin diet breadth started to change around 3.7 Ma, possibly involving increased meat consumption (Sponheimer et al., 2013). Thompson and colleagues (Thompson et al., 2019) hypothesised that meat acquisition, entailing the challenges of scavenging in the form of competition with large carnivores, was necessarily assisted by percussive stone tool technologies to increase extractive efficiency. Percussive tools, however, unlike flaked tools are difficult to recognize and identify archaeologically (Caruana et al., 2014). Although the use of percussive tools by hominins in the Pliocene is theoretically probable, the archaeological data for such behaviours are lacking (but see Harmand et al., 2015 and counter by (Domínguez-Rodrigo and Alcalá, 2016). The known archaeological record begins with the first stone tool technologies, the Lomekwian and the later Oldowan complex that emerged at ~3.3 Ma and ~2.6 Ma respectively (Semaw, 2000; Harmand et al., 2015).

The first flake based technologies, involving the removal of sharp edged flakes through dynamic percussion, by hitting two rocks together, implies that Plio-Pleistocene hominins, unlike any extant apes, understood the fundamental principles of fracture mechanics (Semaw, 2000; de la Torre, 2004; Delagnes and Roche, 2005; Stout et al., 2005; Bril et al., 2010; Nonaka et al., 2010). After 2 Ma a host of technological changes occurred. The bifacial shaping technique at 1.8-0.9 Ma (Howell, 1961a; G. Isaac, 1969; Leakey, 1971; Clark and Kurashina, 1976; Isaac and Isaac, 1977; Clark, 1987; Ludwig and Harris, 1998; de la Torre et al., 2008; Gibbon et al., 2009; de la Torre, 2011; Lepre et al., 2011; Beyene et al., 2013; Gallotti, 2013; Diez-Martín et al., 2014, 2015; Kuman and Gibbon, 2017; de la Torre and Mora, 2018), prepared cores around 300 Ka (Clark, 1970; Leakey, 1976; Kuman, 2001; Beaumont and Vogel, 2006; Tryon et al., 2006; Herries et al., 2009; Wilkins et al., 2010), projectile weaponry and composite tools after 80 Ka (Goodwin and van Riet Lowe, 1929; Wadley, 2007; Wurz and Lombard, 2007; Lombard and Pargeter, 2008; Tribolo et al., 2009, 2012, 2013; Villa et al., 2009; Ambrose, 2010; Högberg and Larsson, 2011; Brown et al., 2012; Conard et al., 2014; Archer et al., 2015, 2016; Soriano et al., 2015; Jacobs and Roberts, 2017) researchers have classified as significant hallmarks, or inflection points in terms of what technology implies about hominin cultural evolution in Africa. Objects representing abstract thought, art and symbolic expression begin to proliferate in the archaeological record only after 100 Ka (Henshilwood et al., 2002, 2004; D'Errico et al., 2005; Parkington et al., 2005; Texier et al., 2013), signifying behavioural traits more likely to be exclusive to modern humans, at least in an African context (Mcbrearty and Brooks, 2000).

Was hominin behavioural evolution a cumulative process that eventually resulted in the emergence of exclusively modern human behaviours? One scenario predicts that technological innovations occurred solely as re-combinations of more simple previously existing tools, a framework of cultural change proposed by Kolodny and colleagues (Kolodny et al., 2015, 2016). It has also been suggested that the manifestation of behaviours unique to modern humans is underpinned by the capacity for cumulative culture (Boyd et al., 2011; Morgan et al., 2015; Tennie et al., 2017). The foundation for cumulative culture involves the modification and improvement of technologies through social learning, from one generation to the next (or horizontally through oblique transmission), which is achieved through process-oriented imitation and teaching, also referred to as high-fidelity transmission (Tomasello et al., 1993; Boyd and Richerson, 1995; Tomasello, 1999; Caldwell and Millen, 2009; Tennie et al., 2009; Whiten, 2011).

Stout and Hecht (Stout and Hecht, 2017) proposed a model wherein the evolution of cumulative culture was a gradual process. For Stout and Hecht, the enhanced connectivity between dorsal and ventral visual streams found in the brains of human and non-human primates were the cognitive prerequisites of cultural learning, and reflect the ancient biological origins of cumulative culture. One line of evidence these researchers used to support their argument was that both the complexity of stone tools and technological systems, as well as their frequencies, were increasing through time.

Many archaeologists share this viewpoint that Pleistocene hominins evolved an early capacity for cumulative culture (McNabb et al., 2004; Whiten et al., 2009a, 2009b; Shipton, 2010; Goren-Inbar, 2011; Whiten, 2011; Kempe et al., 2012; Putt et al., 2014). In particular, many scientists view the emergence of Acheulean stone tool technology in eastern Africa at 1.76 Ma as a cognitive leap in hominin behavioural evolution e.g. (G. L. Isaac, 1969; Gowlett, 1986; Belfer-Cohen and Goren-Inbar, 1994; Klein, 2009; Shipton, 2010; Lepre et al., 2011; Diez-Martín et al., 2015; de la Torre, 2016; Muller et al., 2017; Stout and Hecht, 2017), while social learning is viewed as integral to the transmission of Acheulean tool manufacturing systems between hominins (Wynn et al., 2011).

The precursor of the Acheulean, the Oldowan industry, is usually characterized by relatively simple and expedient flake production systems, and the use of minimally prepared and maintained cores through a knapping process called *débitage* (Stout et al., 2010). The production of Acheulean bifacial Large Cutting Tools (Isaac, 1977) (hereafter “LCTs”) (bifaces and handaxes) remains the most characteristic and recognizable technology by which Acheulean industries are traditionally identified in the archaeological record (Klein, 2009). LCTs are associated with the emergence of broadly systematic bifacial shaping. In the context of LCT production, shaping initiates through the roughing out of selected blanks and is followed by a sequence of finishing stages aimed at thinning, as well as refining bilateral and bifacial symmetry on bifaces (Inizan et al., 1999). It has been suggested that *shaping* is applied to reduce a volume of raw material with a template or a notion of preconceived bifacial form in mind (Inizan et al., 1999). Likewise, the requirements of bifacial manufacturing processes to maintain bifacial and bilateral symmetry on LCTs entailed additional innovations such as the production of large flake blanks out of boulder cores to be used as blanks, which in turn, required changes in raw material procurement patterns (Inizan et al., 1999).

These technological novelties of Acheulean systems have prompted archaeologists to suggest linkages between Acheulean technologies and the onset of several hominin behavioural innovations that are not at all present in the archaeological record preceding the Acheulean. These include the expansion of hominin foraging ranges and mobility, increases in the efficiency of stone raw-material procurement, consumption and use, increased planning depth and the first evident exhibition by hominins of the ability to integrate design templates into stone tool production (Hay, 1976; Isaac, 1977; Gowlett, 1984; White, 1995; Feblot-Augustins, 1997; Potts et al., 1999; Braun and Harris, 2003; Sampson, 2006; de la Torre, 2016).

Acheulean sites have an exceptionally vast temporal and geographic spread. The earliest localities dated to between 1.7-1.0 Ma have been documented predominately in eastern Africa at Kokiselei 4 and Koobi Fora in Kenya, Konso Gardula, Gona, Gadeb and Melka Kunture in Ethiopia, Olduvai Gorge and Peninj in Tanzania (Ludwig and Harris, 1998; Quade et al., 2004; de la Torre and Mora, 2005; de la Torre et al., 2008; de la Torre, 2011; Lepre et al., 2011; Beyene et al., 2013; Gallotti, 2013; Diez-Martín et al., 2015). In South Africa Acheulean, the only dated sites that are older than 1.0 Ma are Sterkfontein (Kuman and Clarke, 2000) and Rietputs (Gibbon et al., 2009; Leader et al., 2016; Kuman and Gibbon, 2017).

Outside of Africa, the early Acheulean is less well represented. There is the site of Ubeidiya in Israel, currently dated to 1-1.5 Ma (Bar-Yosef et al., 1993) and the site Attirampakkam in India, with a suggested age of 1.6 Ma (Pappu and Akhilesh, 2006; Pappu et al., 2011; Akhilesh and Pappu, 2015). Between 1.0 Ma and 0.6 Ma, sites often referred to as ‘classical Acheulean’ or the Middle Acheulean (Kuman, 2014) increase in abundance in comparison to the early Acheulean record of Africa. The latest Acheulean sites are as young as ~250/190 Ka at Duinefontein on the west coast of South Africa and at Saffaqah in the Arabian Peninsula, making the duration of the Acheulean over 1.5 Ma (Klein et al., 1999; Scerri et al., 2018).

In terms of geographic spread, Acheulean-like bifacial technology is present in various other parts of the Old World including northern Africa; the Eurasian countries of France, Spain, England, Italy, Georgia, Korea, China, and India (Frere, 1797; Roe, 1964; Geraads et al., 1986; Bergman and Roberts, 1988; Tuffreau et al., 1997; Haynes et al., 1997; Hou et al., 2000; Piperno and Tagliacozzo, 2001; Raynal et al., 2001; Lioubine and Beliava, 2004; Norton et al., 2006; Pope et al., 2006; Falguères et al., 2006; Petraglia and Shipton, 2008; Zhang et al., 2010; Lefèvre et al., 2010; Pappu et al., 2011; Moncel et al., 2013; García-Medrano et al., 2014; Li et al., 2014; Ollé et al., 2016; Rocca et al., 2016; Daura et al., 2018; Santonja et al., 2018; Shipton et al., 2018).

Some archaeologists have focused on using LCTs as cultural markers, to argue for a single origin of stone artefact technology in Africa, that spread with the dispersal of hominins across the Old World (Clark, 1994; Carbonell et al., 1999; Goren-Inbar et al., 2000; Bar-Yosef and Belfer-Cohen, 2001; Saragusti and Goren-Inbar, 2001; Petraglia and Shipton, 2008). There is a contingent viewpoint that within the temporal and geographic spread of the Acheulean it has not changed significantly through time or across space. This characteristic has prompted researchers to interpret this stasis as approximating a level of standardization in Acheulean technology, equivalent to socially mediated mental templates (Gowlett, 1984; Wynn, 1985; Ashton and McNabb, 1994; Clark et al., 1994; Gowlett, 2006; Pelegrin, 2009; Shipton et al., 2009; Wynn and Gowlett, 2018). As Gowlett (1984) once pointed out, the retention and communication of the mental template of a relatively complex technology required high fidelity transmission, which implies the social transmission of knowledge and ideas, through teaching and imitation (Tomasello et al., 1993) (further discussion on mental templates is in Chapter 1.2.1).

For many scientists, however, cumulative culture and social learning concepts are associated only with humans (Tomasello, 1999; Boyd et al., 2011; Dean et al., 2014; Mesoudi, 2016). Thinkers like Steven Pinker developed the hypothesis that cumulative culture emerged as an abrupt evolutionary by-product when humans entered a specific cognitive niche, in other words, an outcome of an enlarged brain and intelligence (Barrett et al., 2007; Pinker, 2010). Robert Boyd and Peter Richerson articulate this viewpoint slightly differently by proposing that cumulative culture signified a unique event in human evolutionary history when humans entered a cultural niche, and one outcome was the evolution of social learning and imitation (Pinker, 2010; Boyd et al., 2011).

Aspects of chimpanzee behaviours, such as nut-cracking, termite fishing or grooming, that differ at the population level without ecological influence have led some to suggest that aspects of cumulative culture such as social learning and imitation may be found in non-human apes (Boesch and Boesch, 1990; Whiten et al., 1999, 2009a; Boesch, 2003; Horner and Whiten, 2005; Whiten, 2005; Yamamoto et al., 2013; van Leeuwen et al., 2018). Researchers who associate cumulative culture with humans only dispute that these propositions for cumulative culture in other animals do not exceed the inventive capacity of a single chimpanzee, and do not require a successive generation of accumulated knowledge (Dean et al., 2014; Mesoudi, 2016).

In this vein, Claudio Tennie and colleagues hypothesized that chimpanzee cultures and technologies fell in the ‘Zone of Latent Solutions’ (Tennie et al., 2009). The Zone of Latent Solutions is a term that describes technologies or ‘problem solutions’ that do not require high fidelity cultural transmission seen in the cumulative culture characteristic of modern humans. Latent solutions could be independently invented or re-invented by a naïve individual (Tennie et al., 2016, 2017). The enduring homogeneity and low levels of variability within ESA technologies, particularly in the Acheulean, prompted Tennie and colleagues to compare such low levels of variability to chimpanzee technologies. The authors suggested that knowledge of how to make LCTs would not require social learning and could have been independently invented and re-invented (Tennie et al., 2016, 2017).

It is not unanimously agreed, however, that the Acheulean was a static technological system. Many researchers acknowledge or recognize the existence of *slow* change or gradual refinement of Acheulean technologies trough time (Howel and Clark, 1963; G. L. Isaac, 1969; Schick and Toth, 2017). Archaeologists often assume that earlier variants of Acheulean LCTs, those older than 1 Ma, are cruder, less symmetrical and less reduced relative to later Acheulean artefacts (Clark, 1975; Roche et al., 2003; De Lumley and Beyene, 2004; de la Torre and Mora, 2005; Leader, 2009; Beyene et al., 2013; Gallotti, 2013; Diez-Martín et al., 2015; Leader et al., 2016; Kuman and Gibbon, 2017).

Some researchers have suggested that one only sees a significant change around 0.7-0.6 Ma , in terms of cognition and planning depth in Acheulean producing hominins (Wynn, 1985, 1991; Roche, 2005; Beaumont and Vogel, 2006; Stout et al., 2014). Dietrich Stout (2011) for example, defined a demarcation line between the “Early Acheulean”, sites older than 1 Ma, and the “Late Acheulean”, sites younger than ~ .7 Ma. Stout recognized a swathe of traits that differentiate the early from the later Acheulean. These traits include the number of hierarchical production steps, the complexity of each of these steps, and the existence in the later Acheulean of platform preparation prior to removing cross sectional thinning flakes (Stout, 2011; Stout et al., 2014).

The issue of potential temporal variability within the Acheulean raises a number of important questions. If Acheulean technology, and particularly LCTs, were evolving through time, does this imply that this technology represents an accumulation of modifications from one generation to another with relatively minimal loss of information (after (Tennie et al., 2016))? Or could it be that the Acheulean was indeed a latent solution and that variation through time and across space or, more specifically, that *variants* of this technology represent individuals independently inventing these variants (Tennie et al., 2016). If two spatially or temporally separated hominin groups or individuals used similar technologies, but these technologies had very few hierarchically nested steps (Stout, 2011), then it seems plausible that such technologies may have been independently developed by these groups or individuals.

Using LCTs as a marker, the continuity of the Acheulean has largely been assumed, even though the Acheulean as a latent solution – i.e. independently reinvented many times in prehistory - is equally plausible. Both hypothetical scenarios of temporal variability in the Acheulean should be tested for with actual quantitative data. The first steps would be to address the structure of Acheulean LCT variability through space and time, as well as by characterizing spatial and temporal variation in hominin technological organization within the Acheulean, but focusing not exclusively on LCTs.

While the LCT variation and related technological organization among later Acheulean sites has been well documented (McPherron, 2000; Archer and Braun, 2010), the structure of variation within the early Acheulean remains largely unknown. My intention is to contribute to this lacuna in early Acheulean studies, by developing methods in this thesis that will both (1) improve our ability to identify and characterize the Acheulean and (2) will widen our understanding of the spatial and temporal variability within it (see Chapter 3.2.).

The study of technological variation relies both on methods and on theoretical paradigms that have historical traditions and historical contingencies that affect the way we interpret archaeological data today. In the paragraphs below, I will provide an overview of the history of some of the more influential Acheulean research, that I believe are is still influential today.

1.2. Analytical perspectives on the Acheulean

1.2.1. History of research into Acheulean variability

It is probably true for any technological complex with a long research history that identification and classification paradigms for these complexes change substantially through time. A host of different assemblage labels and typological categories associated with the Acheulean represent over 200 years of research. A plethora of terms and classifications have originated as a response to the widening spectrum of variability documented within the Acheulean. These terms reflect also varying pedagogical and methodological backgrounds of researchers, and therefore also different focuses. Following the advice of a Cambridge historian Edward Carr, “Before you study the history, study the historian” (Carr, 1961:38), this section discusses scholars who influenced the way we think about the Acheulean today, as well as their theoretical and methodological paradigms.

A letter by John Frere to the Royal Society of Antiquaries about handaxes found in a clay pit in Hoxne, England, documents the first time, at the end of the 18th century, that these artefacts were mentioned in writing (Frere, 1797). Frere’s discovery was remarkable. First, Frere’s inference of what he thought were ‘weapons…’ belonging ‘…to a very remote period indeed; even beyond that of the present world’ (Frere, 1797:205), remained uninfluenced by the Biblical norms existing at the time. Not only did Frere provide detailed descriptions and magnificent drawings of artefacts, he attempted to reconstruct the stratigraphy and depositional history of these finds, including the assumption that the artefacts could have been manufactured at the site where they were found. Frere’s open mind, curiosity, thorough documentation and unbiased interpretation were way ahead of his time.

When the gravel pit sites were discovered in the Somme Valley of France, about 30 years after Frere’s discovery, Boucher de Perthes, a customs officer and the amateur archaeologist, started working at one of the archaeological sites of Abbeville (Commont, 1909; Tuffreau et al., 1982). At the time of de Perthes, George Cuvier’s ideas of catastrophic events causing faunal extinctions and successions were highly influential. De Perthes suggested that the flint tools from Abbeville belonged to the Celtic populations that occupied the Somme Valley before the biblical flood. De Perthes did not name or categorize the stone tools, yet he observed variability in handaxe forms and attempted to connect these observations to how, what he thought was a ‘delluvial men’, could have been using the tools (Olivier, 1999).

Thirty years later, another French researcher - an ethnologist with anthropological and archaeological training - named Gabriel de Mortillet, came to play a major role in the field of prehistory. During the French Revolution and the Period of Enlightenment ideas about one global history of all humanity influenced De Mortillet, forming his ideology of connecting past and present through the evolution of technology. De Mortillet then shaped the concept of a single continuous progressive evolutionary process from stone tools to iron tools, and contextualized archaeological tools within a succession of cultures that he identified using type fossils (de Mortillet, 1883). De Mortillet named the bifacial handheld artefacts ‘Acheulean’ after the St. Acheuel site in Somme Valley and gave the name ‘Cheulean’ to those artefacts that he believed were older.

At the start of the 20th century Henry Breuil, the catholic priest and archaeologist, developed the first comparative culture-stratigraphic framework. Breuil relied on typology and the idea that what appeared simple and crude must be older than relatively more refined standardized artefact forms, in addition to the idea that technological variability was underpinned by different hominin species (Straus, 1991). Breuil suggested replacing de Mortillet’s term ‘Cheulean’ with the term ‘Abbevillian’ for older handaxe forms, the intention being to honour the work of Boucher de Perthes at the site of Abbeville (Breuil, 1932). Francois Bordes, who was a student of Breuil later explained that the intended difference between the Abbevillian and the

Acheulean was supposed to relate to the use of a soft hammer in the manufacture of Acheulean forms (Bordes, 1968). Research in the 19^{th} - early 20^{th} centuries in Europe created three terms - Acheulean, Cheulean and Abbevillian – to refer to internal variants of what today is known broadly as the Acheulean.

South African research at the end of the 19^{th} century led to a further increase in the number of terms used to refer to Early Stone Age handaxe-based industries, as South African archaeologists were reluctant to borrow names that were developed for European cultural phenomena (Goodwin, 1929). John Goodwin who, along with Clarence van Riet Lowe were the first archaeologists to systematize the stone tool industries of Africa, did not believe that the European naming systems, due to a geographic separation distance of >6000 km for South Africa, was appropriate for naming African materials (Goodwin, 1929). Thus instead of using Palaeolithic terms such as Upper and Lower Palaeolithic, Goodwin together with van Riet Lowe divided archaeological materials into Earlier, Middle and Later Stone Ages (Goodwin and van Riet Lowe, 1929) as a tripartite alternative to Eurocentric classifications of the African archaeological record.

Industries that had bifaces fell within the Earlier Stone Age of Goodwin and van Riet Lowe's system. Older bifacial industries were named the Stellenbosch Industry and were subdivided into Early and Late stages. Younger bifaces became part of the Fauresmith techno complex (Goodwin, 1929, 1935; Goodwin and van Riet Lowe, 1929). The Stellenbosch as a term existed until the 1950s when it was replaced by the Acheulean, although some South African archaeologists still use the term 'Stellenbosch' today. The 'Fauresmith' however, continues to be used widely in the literature, either to denote a final stage of the Acheulean and/or to name transitional industries between the Early Stone Age and the Middle Stone Age (Porat et al., 2010; Herries, 2011).

Unlike the South African scholars, Europeans working in eastern Africa tended to exclusively use European classifications. The renowned archaeologist, Louis Leakey, categorized bifaces that he discovered in Olduvai Gorge from the 1930s onwards into 11 successive stages using the European Cheulles-Acheul terms (Leakey, 1957) (Figure 1). For each stage, Leakey observed certain diachronic morphological changes in bifaces, where relatively younger bifaces tended to have “much more ‘hand-axe’ form” (Leakey, 1936, 1951).

When Mary Leakey took over the Olduvai research from her husband, she established a new nomenclature for Olduvai Gorge. Mary Leakey dropped the use of the Abbevillian and Cheullean terms, but she did not discard L. Leakey’s idea that the earlier Acheulean stages were defined by cruder proto-bifaces. She thus introduced new terms such as the ‘Developed Oldowan’ which was further sub-divided into three stages A-C. Leakey’s various types such as bifaces, proto-bifaces, spheroids, scrapers, discoids in addition to the relative proportions of these types expected for different industries (Leakey, 1971) evolved out of definitions of different aspects of European Palaeolithic industries, originally defined by François Bordes (de La Torre and Mora, 2009).

In her 1971 monograph, Mary Leakey suggested that what she called Developed Oldowan B had broadly the same toolkit as Developed Oldowan A, yet in addition had crude and poorly made bifaces (Leakey, 1971). Developed Oldowan C assemblages had even higher percentages of bifaces. Leakey reserved the use of the term ‘Acheulean’ to refer to assemblages that contained more than 50% of bifaces in their toolkits.

In the 1960s -1970s the typological approach developed after François Bordes became key in the study of certain Acheulean sites in East Africa such as Isimila (Howell, 1961b), Melka Kunture (Chavaillon and Chavaillon, 1980), Gadeb (Clark and Kurashina, 1976, 1979), and Olorgesailie (Isaac, 1977). Bordean typology also underpinned the pioneering work of Maxine Kleindienst in characterizing Acheulean collections based on percentages of bifaces and cleavers (Kleindienst, 1962). Also at this time, Derek Roe defined the LCT categories of Point, Cleaver and Ovate, based on variation in the shape of British handaxes (Roe, 1968).

The era of widening the typological classifications associated with the Acheulean began to cease around the 1980s-1990s. André Leroi-Gourhan - a polyglot, philosopher, ethnologist and archaeologist - who excavated the famous Magdalenian site of Pincevent, remains today arguably the most influential figure behind the methodology of stone tool analysis (Audouze, 2002). The *chaîne opératoire*, introduced by Leroi-Gourhan in the 1950s, was the first approach to treating stone tool production as an all-encompassing dynamic behavioural system, of raw material procurement, and various manufacture, maintenance and discard phases (Sellet, 1993). The goal of lithic analysis within this system was thought to be to perform a 'lithic reading' of an artefact (Pelegrin, 2005) with the objective of evaluating either hominin skill, intentionality or/and conceptualization (Audouze, 2002). *Chaîne opératoire* analysis, which mostly provides a qualitative assessment of lithics has been performed for various Acheulean sites in Africa including Melka Kunture, Gadeb, Peninj, Olduvai Gorge, Mieso, in addition to the European sites of La Noira, La Celle, Caune de l'Arago, Cagny, Charco Hondo (Inizan et al., 1999; Pelegrin and Texier, 2004; de la Torre et al., 2008, 2014; Gallotti et al., 2010; Limondin-Lozouet et al., 2010; de la Torre, 2011; Barsky, 2013; Moncel et al., 2013; Nicoud, 2013; Preysler et al., 2018; de la Torre and Mora, 2018).

Lewis Binford proposed considering material culture as a system, comprising the varied adaptive responses of a given population in the past (Binford, 1964). The idea of looking at culture as an adaptive response is rooted in the field of behavioural ecology (Winterhalder and Smith, 2000). Although Binford was never on the forefront of behavioural ecological theory, his interpretive frameworks were reminiscent of the "optimal foraging model".

Within the optimal foraging framework, the broader central drive of hunter-gatherer society is to optimize ones foraging efficiency while accounting for searching and handling costs (Ugan et al., 2003; Kelly, 2007). Glynn Isaac who originally relied solely on lithic typologies to characterize Acheulean variability became more and more influenced by Binford's work and eventually began to treat artefacts as records of hominin adaptation to the environment. Isaac's drive resulted in the initiation of the first behavioural ecological approach to Early Stone Age lithic analysis in an East African context, that drew on robust quantitative and experimental techniques to characterize lithics (Toth, 1982; Blumenschine et al., 2008; Braun et al., 2008b; Archer and Braun, 2010).

1.2.2. Tea cups and pencils, final forms and dynamic continuums in the assessment of Acheulean LCT variability

As is the case for any object in the world of material culture, LCTs (or bifaces) have a definitive set of properties. For LCTs, the two central properties are size and shape, and the interaction between these dimensions. The ways in which archaeologists attach meaning to these LCT properties vary greatly. Historically, there have been two main schools of thought on interpreting Acheulean LCT variability. Namely, 1) those that view LCT size and shape as the final form or end product of technological intent, and 2) those that focus on treating LCTs as stages or windows onto a dynamic continuum of changes in size and shape.

The first viewpoint treats an LCT as analogous to a tea cup. Once a cup is initially made, its shape and form remain unchanged for much of its use-life, until one day when it falls and is broken into pieces. In contrast, as for viewing LCTs and other lithics as a dynamic system, the late legendary lithic analyst Harold Dibble once proposed that many stone artefacts may be compared to pencils, whose shapes and sizes constantly change throughout their life histories as functional needs arise.

Views of LCTs as the end-products of hominin technological intent, much like tea-cups, are often adopted in studies exploring large geographic scale differences in LCT forms spanning multiple regions, where localized ecological drivers may be less relevant (Roe, 1968; Wynn and Tierson, 1990; Vaughan, 2001; Lycett and Gowlett, 2008; Petraglia and Shipton, 2008; Shipton and Petraglia, 2010). Examples of these approaches to LCT variability include Wynn and Tierson (1990) who studied late Acheulean LCTs from sites in Africa, Israel, India, and England using a shape analysis approach. The authors defined the regional patterning in the distribution of three modal shapes: ‘narrow’, ‘wide’, and ‘normal’. Vaughan (2001) - using the LCT attributes of length and basal shape - adopted the notion that LCT style was a proxy for the population dynamics of different groups. Vaughan applied this approach to LCT contexts from the Early Acheulean to the Late Acheulean of Africa and Europe. Vaughan associated increased temporal variation in European LCT assemblages with continuous migration, or, an increased interaction among existing populations (Vaughan 2001). In a later quantitative attempt to analysing LCT shape, Lycett and Gowlett (2008) proposed that differences in LCT style east and west of the Movius Line and between Acheulean and European artefacts were likely to be underpinned by the intra-regional transmission of knowledge among LCT producing hominins.

As discussed in Chapter 1.1. some researchers tend to focus on LCT spatial and temporal similarities, rather than differences. Viewing LCTs in the archaeological record as intended end products within this framework, implies that information about the mental templates of past LCT production is immediately accessible through observations of the forms recovered from the archaeological record (Gowlett, 1984, 2006; Wynn, 1985; Clark, 1994; McNabb et al., 2004; Pelegrin, 2009; García-Medrano et al., 2018). Desmond Clark, Jacques Pelegrin and John Gowlet all connected conservatism, or standardization in LCT shapes with the ability of hominins to conceptualize mental templates, and tentatively with the origins of language (Gowlett, 1984; Clark, 1994; Pelegrin, 2009). John Gowlett suggested that language would have been advantageous in the mental managing, as well as in the social transmission of complex ideas about LCT manufacture (Gowlett 2006). Furthermore, Thomas Wynn (1985) proposed the concept of equating artefact symmetry with the evolution of intelligence. Within Wynn's viewpoint was the inherent notion that the conceptualization of operational symmetry emerged or evolved with the onset of the Acheulean. John McNabb and colleagues (1994), as an alternative to the word 'template', suggested to use of the term 'conceptual standardization' of LCTs, and proposed the concept of "individualized memic constructs" wherein LCT manufacture entailed the replicating by hominins of what was experienced or observed within their societies.

In stark contrast are approaches that treat LCT shape and size variation as representative of stages, or windows onto a dynamic continuum of size and shape changes, which represent the life histories of different assemblages (Noble and Davidson, 1993; Ashton and McNabb, 1994; Jones, 1994; McPherron, 1994; White, 1995, 1998; McPherron, 1999, 2000; Archer and Braun, 2010; Archer et al., 2015, 2016; Iovita et al., 2017). Artefacts changed in size and shape throughout their life histories, through initial shaping, maintenance and re-sharpening. Artefacts could reasonably enter the archaeological record at any point of their life histories, but likely when they had forms that were no longer desirable to their users (Jelinek, 1976, 1977; Dibble, 1995).

Peter Jones (1994) was among the first to describe the life history stages of LCTs. Addressing the differences between the eastern African Developed Oldowan and early Acheulean techno-traditions, Jones proposed that the two systems represented markedly different re-sharpening stages of single LCTs. Similarly, Mark White (1995, 1998) disagreed with Roe's (1964, 1968) 'oval' and 'pointed' LCT types, and rather interpreted variation between ovate and pointed forms in British LCTs to be underpinned by a combination of variability in initial blank form as well as raw material type. The influence of raw material variability (type and form) on LCT shape was also addressed by Ashton and McNabb (1994).

In contrast, Shannon McPherron (1994, 1999, 2000) quantified how LCT shape changed with reduction trajectories, through artefact resharpening. Specifically, McPherron suggested that as reduction progressed, elongated LCTs became rounder. Unlike White (1995, 1998) and Ashton and McNabb (1994), in the McPherron model, the effect of raw material on LCT form was minimal (McPherron, 1999). Archer and Braun observed a similar pattern of artefact shape changes with reduction in southern African LCTs at Elandsfontein (Archer and Braun, 2010). Gonen Sharon, however, made the point that the reduction model did not work for Acheulean cleavers, as these artefacts tended to be minimally shaped after initial manufacture (Sharon, 2010).

Chapter 3.2. of this dissertation contributes to this discussion by providing the first appraisal of LCT variability within the early Acheulean. While both interpretive perspectives (LCTs as final forms and LCTs as windows onto a dynamic system) are considered as possible alternatives, understanding the likelihood of one explanation was largely contingent on evaluating the other. What is meant by this is that it was important to first understand and quantitatively isolate differences related to manufacture and maintenance of LCTs. Once this was done the remaining residual variance could be investigated and possibly attributed to stylistic differences that related to the intended forms of the hominin makers.

1.2.3. Spatial perspectives on the Acheulean, lithic proxies for technological behavioural change, and classical models of technological organization

A behavioural system is what Lewis Binford referred to as a subsistence-settlement system, that he formulated through extensive ethnographic research of Nunamiut (Inuit group) hunters in Alaska (Binford, 1978, 1979, 1980). For Binford, understanding raw-material procurement, manufacture and the use of tools was critical to establishing the functional roles of different sites, and was critical also to distinguishing different technological organization patterns within these subsistence-settlement systems.

In the 1978 paper “Dimensional Analysis of Behavior and Site Structure: Learning from an Eskimo Hunting Stand”, Binford presented a detailed account of the technological organization around Nunamiut hunting stands. Binford classified different types of personal or shared items entering the stand in several categories. These included firstly site-specific items shared by a number of individuals that were likely expediently used such as anvils. And secondly, this included objects curated at a site, and then stored, such as cutlery, pots, sugar and coffee. Binford documented likelihoods of which kinds of artefacts would enter the archaeological record. For instance, site-specific objects were predicted to always make it into the archaeological record. Another category was personal items of minimal use. Some personal items of minimal use and low value, such as metal files or hones, could have entered the archaeological record for instance at times when these items were stored in a cache. Other, more precious items, such as a pair of binoculars, were curated by an owner, and had a lower probability of entering the record.

Nunamiut technological organization also included items of frequent use. Some items such as food packaging were frequently used, and therefore had a good probability of entering the archaeological record. Other items such as individual hunting gear, though frequently used, were less likely to enter the record. Binford hence warned, “The particular patterns of technological organization conditioned the degree to which items did not go into the archaeological record as a direct consequence of their use.” (Binford, 1978:343). Even if an activity such as butchering was taking place at a site, there would not necessarily be artefacts discarded that related to this particular activity. Another important message of the Nunamiut study was that a slight change in the organizational system of a given set of behaviours, for instance, if Nunamiut hunters used personal cutlery and cups instead of sharing them among the group, would result in these objects being less likely to be present in the archaeological record of the hunting stand.

I do not suggest using Binford’s data as a direct behavioural analogy for Acheulean landscape use. It would be problematic to conduct a comparison of modern hunter-gatherers with a group of hominins whose subsistence strategies remain largely unknown (Thomspon et al., 2019). Binford’s research, however, provides a generalized guide or a set of axioms for dissecting the complexity of technological organization, and the resulting effects on the archaeological record. Binford’s studies are also a cautionary tale in the interpretation of the technological organization of Acheulean hominins.

These ethnographic observations show just how easily behaviours could be misinterpreted from the material remains left behind by our own species, *Homo sapiens*. For example, the reliance on a single tool type to interpret behaviour, such as an LCT, might lead to the oversimplifications of technological organizations. LCTs are the most characteristic and recognizable attributes of the Acheulean, but they are only one of the many constituents of the Acheulean behavioural system. On their own LCTs may not be revealing about all aspects of hominin subsistence and settlement. Other key elements of the Acheulean system may be the flakes relating to biface manufacture and maintenance, as well as large flakes and boulder cores used for making blanks, which tend to be ignored in Acheulean contexts, but which may well have different landscape scale distributions to LCTs.

There are also components of the Acheulean that have little connection with bifacial production, nevertheless, such elements tend to co-occur at the same archaeological sites as bifaces. For instance, cleavers undergo similar production steps to bifaces, yet are different enough in form for researchers historically to have classified them as different components of the toolkit (Inizan et al., 1999; Sharon, 2010). There are also cores in the Acheulean that are too small to be used as blanks for bifaces (de la Torre, 2009, 2011; Leader et al., 2016). To fully understand aspects of Acheulean hominin mobility, subsistence and landscape use, these different technological elements and their interactions need to be investigated together.

The procurement and selection of blanks constitutes the first phase of LCT manufacture (Stout, 2011; Preysler et al., 2018). Although slabs and cobbles in addition to flakes served as blanks for Acheulean bifaces in certain contexts (Lepre et al., 2011; Moncel et al., 2013), in many instances the initial blank used is largely unrecognizable on more extensively reduced LCTs. What is clear is that hominins predominantly used large flakes to make bifaces in all contexts where blank selection patterns have been studied in detail(G. Isaac, 1969; Goren-Inbar and Sharon, 2006; Shipton et al., 2009; Sharon, 2010).

Various proxies have been used to identify *in situ* large flake production. These include the presence of boulder cores and/or flakes that are larger than 10 cm in maximum dimension at Acheulean sites (Kleindienst, 1962; G. Isaac, 1969; Sharon, 2010). In Oldowan sites such as Gona (OGS-7, EG-10, EG-12), Omo, West Turkana (Lokalalei 2C), Koobi Fora (KBS sites), flakes on average tended to be considerably smaller than the 10 cm blanks found in Acheulean contexts. Eastern African Acheulean sites in contrast, have the first evidence for the systematic, use by hominins of large flakes. Although the sizes of Acheulean flakes are highly variable at the assemblage level, and occasionally LCTs were produced on flakes smaller than 10 cm, available data indicate that there was a dramatic increase in the size of the flakes used from the Oldowan to the Acheulean (Sharon, 2010; Braun, 2015). Some of the key examples of earlier sites with large flake production are Olduvai Gorge, Rietputs, Koobi Fora, Peninj, as well as many younger localities such as Kariandusi, Isimila, Gadeb, Montagu Cave, Elandsfontein, Melka Kunture, Gesher Benot Yaqov, Amanzi Springs, and outside Africa Gesher Benot Yaqov, Isampur Quarry, Caune de l'Arago (Howell, 1961b; Keller, 1973; de la Torre et al., 2008; Archer and Braun, 2010; de la Torre, 2011; Shipton, 2011; Barsky, 2013; Gallotti, 2013; de la Torre and Mora, 2018).

Experimental research has shown that flakes with symmetrical teardrop shapes facilitate the efficient manufacture of bilaterally symmetrical bifaces, thus decreasing overall production time through investment in blank production (Jones, 1994; Sharon, 2008; Shipton et al., 2009). Since flake removal sequences on early Acheulean LCTs are rarely extensive, and flake scars are often non-invasive, much importance is attached to the initial blank production within the early Acheulean (Roche et al., 2003; de la Torre and Mora, 2005; Leader, 2009; Gallotti, 2013; Diez-Martín et al., 2015; Leader et al., 2016; Kuman and Gibbon, 2017). Raw material economic efficiency is another advantage of flake blanks over cobble and slab blanks. For instance, 5-10 large flake blanks can be removed off a single boulder core (Madsen and Goren-Inbar, 2004). Importantly, sizeable flakes were not only destined for the manufacture of bifaces. Cleavers, although only rarely associated with early Acheulean industries, are tools that are made on flake blanks with predetermined morphologies and edges that remain unretouched (Inizan et al., 1999).

It has been argued by some that the understanding of a large flake production coupled with increased technical capacities associated with the Acheulean, liberated hominins from a prior dependency on river cobbles or slabs (Sharon, 2008). An alternative perspective is that because rivers do not have the carrying capacity to transport large boulders that are needed for large flake production, this situation of raw-material stress forced hominins to exploit other sources such as primary outcrops. Many researchers agree that the raw material demands of large flake production must have led to the shifts in raw material procurement and transport which are associated with the onset of the Acheulean, which in turn had clear effects on hominin mobility patterns (Hay, 1976; White, 1995, 1998; Feblot-Augustins, 1997; Potts et al., 1999; Hallos, 2005; Sampson, 2006; Blumenschine et al., 2008; Archer and Braun, 2010).

Following blank production, there are a series of steps that involve manufacturing the LCT using what is known as the *façonnage* or the 'shaping' technique (see Chapter 1.1) (Inizan et al., 1999). Bifacial flakes – the flakes that are produced through *façonnage* - tend to have a set of characteristic morphologies that result from technological constraints imposed by the process of bifacial shaping. These flakes tend to be long and wide, with relatively low masses, small platforms, concave profiles and are thin relative to *débitage* flakes (Dag and Goren-Inbar, 2001).

The ability to recognize and distinguish *débitage* from shaping flakes in the Early Stone Age exposes a range of behaviours that would be otherwise hidden. Flakes belonging to different shaping stages, including roughing out, thinning and edge regularization are informative about whether manufacturing or maintenance or both activities have taken place at a given site. Broadly the ability to differentiate shaping flakes has three important potential applications in the Acheulean. Namely, 1) to understand whether, and to what degree, Early Stone Age collections without characteristic LCTs may be associated with LCT manufacture and use, 2) to better characterize Acheulean flake assemblages where bifacial shaping products co-occur with core and flake technologies and, 3) to contribute to our understanding of variability in Acheulean site function within a landscape context. Novel quantitative methods for characterizing shaping versus *débitage* flakes, within the framework of Acheulean variability and landscape use, is a key theme in this thesis that will be fleshed out in Chapter 3.1. and Appendix 1.

With regard to the first application (1), numerous African sites that fall within the period conventionally associated with the Acheulean have few to no LCTs. For instance, the Nadung'a 4 locality in West Turkana is a Middle Pleistocene site dated to ~700 Ka, a period wherein one would expect bifacial industries. Yet artefact assemblages at Nadung'a 4 contain denticulates and notches, but no LCTs (Delagnes et al., 2006). Likewise, layers V-5 and V-6 at Gesher Benot Ya'aqov, Israel, contain no LCTs but have been assigned to the Acheulean through a qualitative characterization of technological aspects of the flake collections (Goren-Inbar and Sharon, 2006). The absence of LCTs at many Middle Pleistocene sites in eastern Asia is significant (Lycett and Bae, 2010), and the presence of relatively crudely shaped LCTs that some would term questionable at certain Korean sites such as the Imjin/Hantan River Basin (Norton et al., 2006) would benefit from an analysis of these assemblages from the perspective of the flakes.

It has been argued that hominin technological evolution in the Early Stone Age had a more-or-less linear trajectory and that the emergence of bifacial technology coincided with the demise of core and flake technology (Foley and Lahr, 1997, 2003). The occurrence of several Pleistocene sites where simple core and flake Oldowan-like products, were present alongside classical Acheulean pieces challenges the linear trajectory theory. However, to recapitulate, Oldowan-like core and flake technology is markedly different from boulder cores used for a large flake blank production that is associated with the LCT *chaîne opératoire*.

De la Torre (de la Torre and Mora, 2005, 2018; de la Torre et al., 2008; de la Torre, 2011), in describing these type of cores from Acheulean localities of Peninj, Gadeb and EF-HR, has suggested that they belong to a separate *chaîne opératoire (*not related to LCT *chaîne opératoire)*. Other examples of Oldowan-like cores occurring within Acheulean contexts have been described at Olorgesailie, Kenya (Potts et al., 1999), as well as at the Middle Awash, Ethiopia (de la Torre, 2011). This demonstration that classical Oldowan and classical Acheulean characteristics had the potential to co-occur with one another to varying degrees in the ESA, suggests that interrogating the behaviours underpinning these patterns would benefit from a quantitative model to better understand Early Stone Age flake production systems.

To summarize, Acheulean technological organization included both large flake blank elements and large boulder cores. The shift towards large flake production had consequences for changes in hominin mobility patterns, in provisioning systems and in landscape use patterns (Potts et al., 1999; Hallos, 2005; Blumenschine et al., 2008; Presnyakova et al., 2018). LCTs and shaping flakes are two additional components of the Acheulean technological system. Differentiating shaping flakes from *débitage* flakes may provide insight onto manufacturing and maintenance practises that either took place at a given place on the landscape or not, and thus may be revealing about variation in site function and landscape use patterns.

Acheulean assemblages that have combinations of Oldowan-like *débitage* technologies together with LCT technologies, assemblages with large flake blanks and/or shaping flakes but no LCTs, and assemblages that have LCTs but no shaping flakes all have key information about the organization of hominin technology in a landscape context. Quantitative models for differentiating these assemblages will therefore be key to investigating Acheulean hominin landscape use, which provides the impetus for models developed in Appendixes 1 and 2.

The interaction between hunter-gatherer mobility, technological organization and landscape use has been another focus of Binford's work that is articulated in his discussion of curated versus expedient technologies (Binford, 1978, 1979). Binford contrasted gear that was expediently produced at a site, referred to as 'situational gear', with 'curated gear', the latter being items that were produced well in advance, and anticipation, of future use (Binford, 1979:269).

Binford argued that technologies intended for future use only appeared during the Upper Palaeolithic. Subsequent studies have supported this view by arguing that advanced cognitive abilities associated with planning depth only emerged with behaviourally modern humans (Binford, 1985; Toth, 1987; Roebroeks et al., 1988; Shick, 1988; Kuhn, 1992; Noble and Davidson, 1996; Mcbrearty and Brooks, 2000). Conard and Adler presented one of more recent studies that may be understood to contradict this view (Conard and Adler, 1997). The researchers analysed refits and raw material sources at the Middle Palaeolithic site of Wallertheim, Germany. They documented an interaction between raw material type and stage of reduction at the site. For example, for artefacts made on rhyolite only resharpening and maintenance stages of reduction were present (Conard and Adler, 1997). The authors argued that Neanderthals had curated technologies and therefore had capacities for long term planning, which extended beyond activities undertaken within a single day. Turq and colleagues also argued for fragmentation of stone working in space, time, and social dimensions during the Middle Palaeolithic of Western Europe. Turq and colleagues suggested that Neanderthals were using highly mobile foraging strategies (Turq et al., 2013). Yet other scholars have linked curation and depths of planning to the use of exotic raw materials by Neanderthals, that sometimes were procured over distances as far as 100 km from the Middle Palaeolithic sites (Fernandes et al., 2008; Spinapolice, 2012). The focus on comparing and contrasting Neanderthals and Homo sapiens cognition and behaviours, and in particular the abilities to plan in significant spatial and temporal depth, has been a topic that received considerable attention e.g. (Wynn and Coolidge, 2004; Burke, 2012).

New data on the transport of tools, food, or both among chimpanzees, presents a very different perspective on the debate on curated technologies, and their evolutionary history (Carvalho et al., 2008). For example, recently Proffitt and colleagues presented evidence of chimpanzee artefact curation at the Panda 100 archaeological site (Proffitt et al., 2018). Indications that both Neanderthals and possibly even non-human primates planned their activities in a spatially and temporally fragmented way across the landscape contrasts with Binford’s proposal that planning depth was a capacity exclusive to modern humans.

Evidence that curation took place, does not necessarily imply a planning depth equivalent to Nunamiut hunter-gatherers described by Binford. In this vein, Conard and Adler (1997) suggested viewing curation as a continuum rather than a binary variable, i.e. presence or absence, in any system of technological organization. Although Neanderthals, modern humans, archaic hominins and even non-human primates might have curated their technologies to some degree, patterns of how technology was curated and organized most likely differed significantly between these species. Was curation involved in Acheulean contexts and what are the spatial predictions for it?

The dichotomy of curated versus expedient assemblages is reflected spatially in the concept of ‘site fragmentation’, a term that is used mostly within Early Stone Age contexts. Site fragmentation refers to spatially structured artefact discard patterns, which appears archaeologically as if artefact manufacture cycles at different sites have been interrupted (Hallos, 2005). Several Acheulean sites document evidence of reduction sequence segmentation. LCTs from Kilombe and Olorgesailiein Kenya, numerous sites in South Africa, and at Aroeira in Portugal, were transported to the sites in fully manufactured form, and were only re-sharpened at these sites (as opposed to being made there) (Isaac and Isaac, 1977; Crompton and Gowlett, 1993; Braun et al., 2013; Presnyakova et al., 2015; Daura et al., 2018).

However not all Acheulean sites have fragmented sequences. La Noire in France, dated to ~ 0.7 ma, documents a complete LCT reduction sequence, while a group of late semi-contemporaneous Acheulean sites at Mieso, Ethiopia have a combination of complete and fragmented sequences (Moncel et al., 2013; de la Torre et al., 2014). Chapter 3.3. will further address the issue of the organization of technology among Acheulean hominins, by comparing and contrasting the details of hominin technological organization in early and late Acheulean sites.

1.3. Models of the emergence of the Acheulean

It is widely accepted by scientists that the emergence of the Acheulean signified the onset of a novel set of hominin behaviours. The cognitive implications and adaptive benefits of these behaviours, however, remain a topic of ongoing discussion and even contention (Chapter 1.1.). The structure of diachronic and synchronic variability within the Acheulean, and how this variability is manifested in the organization of Acheulean technology has potential to elucidate the broader significance of the Acheulean for hominin behavioural evolution (Chapter 3.1. and 3.2.). There are, however, additional themes and issues that researchers have raised in the context of the Acheulean.

While archaeologists have documented the earliest known appearance of the Acheulean, ~1.78 Ma in Kenya, the triggers for, or drivers of, the emergence of this technology remain ambiguous. As behavioural adaptations are influenced by the environments in which organisms live, a link between environmental change and hominin behavioural evolution has been historically argued (DeMenocal, 2004, 2011). There were several attempts to link (1) three major climatic shifts, and (2) the related establishment of dryer more open conditions in Africa 2.7, 1.7 and 1 Ma, to speciation and extinction. In other words, climate has been linked to so-called 'turn-over events' in the mammalian community, as well as to important technological shifts including the emergence of the Acheulean (Vrba et al., 1989; Vrba, 1993;

DeMenocal, 2011; Lepre et al., 2011). Diez Martin and colleagues argued that appearance of the Acheulean in Olduvai Gorge was related to an aridification trend that initiated around 1.7 Ma on the African continent (Diez-Martín et al., 2015).

Contrasting studies, however, demonstrated that local environments in Africa were much more variable and interchangeable than the global patterns predict (Behrensmeyer et al., 1997; Bobe et al., 2002; Trauth et al., 2009; Joordens et al., 2011; Potts, 2013). Mammalian communities were likely responding to local climatic fluctuations, suggesting that variable environments triggered rapid adaptive responses (Potts, 2013). Unstable environments and volatile habitats almost certainly had an effect on hominin behavioural change, however, identifying a single event or a set of events that brought on adaptive responses in the form of the Acheulean, in several parts of Africa, is challenging.

David Braun and colleagues connected local environmental fluctuations at Koobi Fora, Lake Turkana - in particular changes in fluvial patterns - to changes in raw material availability and subsequent changes in Oldowan core reduction patterns (Braun et al., 2008b). It is possible that similar mechanisms could explain the emergence of the Acheulean in this region. Changes in fluvial patterns related to volcanism, described by Braun et al. (2008), could have affected the fluvial transport of cobbles at different times, changing raw material availability for hominins. The reasoning is that because hominins were unable to rely on secondary raw material sources from rivers, they would have had to search for alternatives sources, such as primary outcrops.

One as yet untestable hypothesis is that the combination of the forced exploitation of primary sources, and contingent longer raw material transport distances, could have led to the emergence of the large flake Acheulean. The reverse scenario is possible too. The shift towards large LCTs may have triggered the need for large flake blanks and exploitation of primary sources. This is a situation where the conflation between cause and consequence is difficult to dissect with available archaeological data, and that the mechanisms that led to the emergence of the Acheulean may always be complicated to decipher.

Then again, the mechanisms of change may have been variable and context specific, and may be linked with the structure of technological variability discussed in Chapter

1.1. If the Acheulean was a single technological development, a process of common descent, gradually changing through time, then establishing a single causal mechanism would solve the issue of emergence. However independent reinventions of Acheulean like technologies, that occurred many times in Pleistocene, could have many causal explanations.

There have been attempts to link the emergence of new hominin species with the appearances of new technological innovations, and the Acheulean is a case in point (Lepre et al., 2011). At the time when the Acheulean emerged, several hominins co-existed in Africa. These species included *Paranthropus boisei, Paranthropus robustus, Homo habilis, and Homo erectus* (Asfaw et al., 2002; Richmond et al., 2002; Brown et al., 2004; Potts et al., 2004; Wood and Constantino, 2007; Antón, 2012; Leakey et al., 2012; Antón et al., 2014). Current fossil data suggest that by 1.4 Ma, *Homo habilis, and Paranthropus robustus* were already extinct (Feibel et al., 1989; Wood and Richmond, 2000; Spoor et al., 2007) and by 1 Ma *Paranthropus boisei* was also extinct (Suwa et al., 1996; Wood and Richmond, 2000). The extinction of these hominins, while the Acheulean technological system was persisting, in addition to a small number of associations between Acheulean artefacts and *Homo erectus* fossils (Potts et al., 2004) lead to the suggestion that *Homo erectus* was the sole hominin responsible for the production of the Acheulean.

The increased cranial capacity of *Homo erectus*, its derived pelvis and femur, elongated limbs, modern like posture, as well as behavioural traits such as increased home range, and the dispersal of this species out of Africa may be suggestive of an association between this hominin and the behavioural repertoire associated with the Acheulean (Wood and Richmond, 2000; Klein, 2009).

However links between hominin species and technological systems, for the archaeological record in general, are often weak, and the association between *H. erectus* and the Acheulean is no different. It is rare to find hominin fossils and artefacts in a single stratigraphically associated context. In sites where such discoveries are made, questions are often raised as to why hominins died – or how they ended up - at localities where they made and used stone tools.

In this vein, there are sites in Europe and Africa where *Homo heidelbergensis* fossils were found in close proximity to Acheulean artefacts. There are *Homo* *heidelbergensis (or early Homo sapiens)* from Bodo, Middle Awash with an approximate age of 0.6 Ma (Rightmire, 1995), Lake Ndutu from Tanzania and the Saldanha skull from Elandsfontein. Both fossils are potentially >400 Ka (Singer and Wymer, 1968). Additionally there is a tibia from Boxgrove, England (Roberts et al., 1994), a skull and other fossil fragments from Caune de l'Aragua, France dated to ~600-300 Ka (De Lumley and De Lumley, 1973; Falguères et al., 2004), and possibly a femur shaft from Notarchirico, Italy (Klein, 2009). In addition there are skull fragments from Swanscombe, England (Stringer and Hublin, 1999).

Some paleoanthropologists, however, consider *Homo heidelbergensis* a problematic category where possibly several middle Pleistocene hominin species have been inappropriately lumped. In consequence, there is a suggestion that the term 'middle Pleistocene hominin' instead of *Homo heidelbergensis or early Homo neanderthalensis* (Klein, 2009; Harvati et al., 2010) may be more appropriate. Recently a 400 Ka old cranium was presented from the site of Aroeira-3 in Portugal, which is one of the less questionable associations of a specific hominin with Acheulean bifaces. The latter cranium had a combination of primitive and derived features that did not allow researchers to place it in either Homo *neanderthalensis* or *Homo heidelbergensis* categories (Daura et al., 2017).

In sum, the fossil evidence suggests that *Homo erectus* could have been a manufacturer of the Acheulean. Later on, more derived *Homo heidelbergensis* could also have been associated with the Acheulean. There are also as yet unclassified taxon groups of Middle Pleistocene hominins, such as Aroeira-3, that could have been producers of the Acheulean.

CHAPTER 2. RESEARCH QUESTIONS, OBJECTIVES AND MATERIALS

2.1. Questions and Objectives

2.1.1. Methodological questions, assumptions and objectives

For anthropologists who study the ethnographic present -current cultures, practices and traditions - material culture represents only one of many avenues of research. In contrast, for archaeologists interested in the evolution of behaviour, material remains are the key, if not the only, source of information. Being the sole source of information for thousands and even million of years of behavioural evolution, stone tools are important as they are incredibly abundant and present archives of unalterable and irreversible actions made by hominins. Following Pelegrin, the action of fracturing a stone nodule with a hammerstone cannot be undone (Pelegrin, 2005). Stone tools are reflective of procurement, reduction, maintenance, use and discard decisions, and serve as means to document the interactions between hominins and their immediate environments (Spier, 1970; Nelson, 1991; Bousman, 1993; Pelegrin, 1993; Bleed, 1997; Inizan et al., 1999; Braun, 2006; Carr and Bradbury, 2011a). Researchers have also employed stone artefact analysis to access patterns concerning mobility and residential variability (Binford, 1979; Weniger, 1987; G. Enloe and David, 1989; Féblot-Augustins, 1993; Blumenschine et al., 2012; Larionova, 2016), hunting practises (Bleed, 1986; Lombard, 2005; Wadley and Mohapi, 2008; Rots et al., 2017) and between group social exchange networks (Whallon, 2006; Wilkins, 2010; Brooks et al., 2018).

Within this framework, this thesis will also make a methodological contribution to our knowledge about the Acheulean, by developing new statistical approaches to analyzing variability in Acheulean technologies. These quantitative avenues will focus on LCT variability and on identifying subtle aspects of variability in technological organization that are largely inaccessible with conventional approaches to the study of stone tool variability.

Although, the fragmentary nature of the archaeological record inhibits the potential relevance of foraging models formulated on the ethnographic present, the fundamental principle that hominins relied on technology to maximize their adaptive fitness still applies, and that this process involved several trade-offs regarding the management of energy expenditure (Bright et al., 2002; Ugan et al., 2003).

For example, a principle that applies to the Early Stone Age is that hominins endeavoured to minimize the costs incurred in the acquisition of raw material, and thus attempted to maximize the number of flakes/tools that could be made from a given volume of raw-material, of course within the constraints of the tool morphologies they were after e.g. (Braun and Harris, 2003). Within the behavioural ecological approach, the interaction between environment and technology takes priority over potential social drivers (Braun, 2006), which contrasts with the *chaîne opératoire* approach to lithic analysis that places primacy on the social dimensions of tool production (also introduced in Chapter 1.2.). The emphasis of the *chaîne opératoire* approach is on individual intent, skill and cognition.

This contrast between behavioural ecology and *chaîne opératoire* results in different null hypotheses for the archaeological record. For *chaîne opératoire*, the null hypothesis assumes that cultural variation exists (i.e. is the most parsimonious explanation for archaeological variability). For behavioural ecology the null hypothesis assumes that there is no cultural variation up until the point where variation can no longer be explained by ecological factors (Stout et al., 2010).

One tenet of the approach I have adopted in this thesis is aligned with *chaîne opératoire*, and focuses on the whole operational sequence of tool production from procurement to discard (Inizan et al., 1999). The theoretical basis that I adopt for interpreting documented variability, however, is influenced strongly by behavioural ecology.

I relied on Glynn Isaac’s proposal of studying lithic variability through his “Method of Residuals” (Isaac, 1986). The Method of Residuals proposes interpreting identified artefact variability in a series of steps, by looking first at the most parsimonious explanation for the documented variance (Li et al., 2014). Once the effects associated with this first level have been investigated, the residual variance – in the next step - is interpreted against the second most parsimonious variable. In this scheme, the influence of variables such as raw material variability and reduction intensity is examined first, and the remaining variance that these variables fail to explain would be evaluated against predictors for which archaeological proxies are largely unavailable, such as cultural traditions and cognitive abilities.

The first methodological objective of this thesis was to quantify variation between flake production strategies identified within simple, typical Early Stone Age core and flake industries, and flake production identified within the application of roughing out and bifacial shaping strategies.

Stone flakes are the only artefacts that can be traced unequivocally to the actions of a single individual, whereas handaxes, cores, retouched tools, etc. were potentially handled by multiple individuals. Flakes are also the most abundant artefact in the archaeological record for almost all of human evolutionary history. Every manipulation with a stone tool that involves chipping - a blank production, an LCT production, a blade production, or a flake production - results in detachment of a flake.

Although the Oldowan and the Acheulean belong to two different knapping processes - *débitage* and the *façonnage* – both processes resulted in flake removals. Each knapping process, however, had very different requirements. For bifaces the central objectives were the maintenance of bifacial volume and symmetry in bifacial shaping (Inizan et al., 1999). The length and shape of the working edge of flakes relative to their morphology, and the maintenance of core edge angles were more central focuses in flake *débitage* systems (Braun and Harris, 2003). It is reasonable that these very different fundamental reduction objectives resulted in quantifiably different sets of products and waste. The first hypothesis of this thesis was that ESA core and flake shapes, and Acheulean LCT flake shapes could be distinguished from one another using quantitative methods (Chapter 3.1.1. and Appendix 1).

The second methodological objective was to develop a 3-dimensional geometric morphometric analytical framework (hereafter “3DGM”) for the analysis of early Acheulean LCTs. The broader objectives here were to investigate the behavioural patterns underpinning complex interactions between artefact size and shape, reduction, and a series of other independent variables. Despite the quantitative focus in the methods of the individual studies, this work additionally employed qualitative data too. Descriptive analysis provides insights into the central aims of production within the lithic *chaînes opératoires*, while the combination of qualitative and quantitative data (e.g. 3DGM) serve as independent but complementary avenues of analysis (Roche and Lefevre, 1988; Boëda et al., 1990; Geneste, 1991; Pelegrin, 1993; Inizan et al., 1999).

3DGM provides a means of documenting artefact shape variability to a level of detail that may not easily be visible to, or measurable by, lithic analysts using traditional descriptive and linear measurements. Statistical analyses then allow one to model variation in shape and size against an independent range of predictors. Typical examples of important independent variables in 3DGM studies on stone artefacts include reduction intensity, spatially distinct use-wear as well as variation related to knapping skill and style (González-José and Charlin, 2012; Archer et al., 2016).

Conventional GM methods were fully developed in the study of biological shape variation among bones and teeth, and proceed through the analysis of homologous landmark configurations that closely approximate the overall shape of objects (Slice, 2007; Mitteroecker and Gunz, 2009; Baab et al., 2012; Gunz and Mitteroecker, 2013).

The more recent development of semi-landmark protocols allowed, for the first time, a statistical description of the interior zones of curves and surfaces of biological specimens where homologous landmarks may be rare or absent (Gunz et al., 2004; Slice, 2007). In comparison to biological specimens, stone tools generally have very few if any homologous features, and one is left to rely on technologically and functionally correspondent features for stone tool orientation. The development of semi-landmarks enabled the application of GM to stone artefacts and, in the past decade, the number of GM applications in lithics studies has grown exponentially (Lycett et al., 2006; Buchanan and Collard, 2007; Lycett, 2007; Lycett and Gowlett, 2008; Archer and Braun, 2010; Buchanan et al., 2012, 2015; González-José and Charlin, 2012; Lycett and Von Cramon-Taubadel, 2013; de Azevedo et al., 2014).

A small number of previous 3DGM biface studies focussed on automated orientation and landmarking protocols (Archer et al., 2015, 2016). These previously proposed approaches proved, however, to be wholly inappropriate for Early Acheulean bifaces. The reason for this is that early Acheulean LCTs often have numerous surface irregularities, and usually have one or more highly convex surfaces or faces. The asymmetric characteristics of the early Acheulean specimens studied here, therefore, required the development of an approach where all specimens were manually oriented. Further, at the outset, all landmarks on geometrically correspondent curves were manually digitized. For this reason, a new GM protocol was developed in the framework of this thesis. This new protocol was specifically designed to capture the details of variation in three-dimensional early Acheulean biface shape (Chapter 3.1.2. and Appendix 2).

2.1.2. Behavioural questions and objectives

The above-described methods were strictly designed with the purpose to address a series of questions related to hominin behaviour from a quantitative perspective. Much of the research on early Acheulean assemblages older than 1 Ma has focused relatively exclusively on documenting the diachronic variability of this technological system (Roche et al., 2003; de la Torre and Mora, 2005; de la Torre et al., 2008; de la Torre, 2011, 2016; Lepre et al., 2011; Beyene et al., 2013; Gallotti, 2013; Diez-Martín et al., 2014, 2015; Gallotti and Mussi, 2017). However, I believe strongly that before addressing technological change through time it is imperative to know how much technological variability one could expect to see within this complex across a relatively short time frame, across a landscape at a specific time for example. Although synchronic variation in the later Acheulean, i.e. younger than 1 Ma, has been addressed (McPherron, 1999; Archer and Braun, 2010; de la Torre et al., 2014), the extent and nature of variation in the early Acheulean have not yet been investigated.

Thus, the question raised in this work was whether LCTs varied substantially in terms of shape, size, and technology between and within early Acheulean sites at Koobi Fora, the research locality in northern Kenya. The null hypothesis was that no morphological variation existed between the analysed sites. If documented, what behavioural factor(s) would explain morphological variability within contemporaneous early Acheulean assemblages? Here I adopted Isaac's, already described, step-wise research approach to first focus on the most parsimonious explanations for artefact variation such as reduction intensity.

The combination of a flake focused approach with the 3DGM method targeting tools (LCTs) enabled me to address a broader set of questions about hominin landscape use, site function and technological organization from multiple analytical perspectives. The ability to differentiate and identify shaping and non-shaping flakes at a single site enables the estimation of whether certain technological activities took place there or not - e.g. a binary decision about LCT manufacture - providing a means to draw quantitative inferences about site function across the landscape.

Documenting inter and intra site variation in LCT morphologies is equally powerful in the assessment of variability in site function and landscape use. The isolation of variation in LCTs related to manufacture and maintenance activities allows one to visualize the trajectories of shape and size change that existed within the application of a certain production method. Importantly, it is discussed later in the thesis that a discrete method was practised at Koobi Fora, making these visualizations particularly revealing in inter-site comparisons. Depending on the production stages present at a given site, conclusions can be drawn about the role that site played in landscape use patterns (see Appendix 2).

The combinations of inferences drawn from both flake and tool datasets, and the nuanced interactions between these different technological elements as revealed by the quantitative models presented below, will build on and contribute to existing knowledge about the organization of Acheulean technology within a landscape context (Chapter 3.3.). Using assemblages from both the early Acheulean sites from Koobi Fora and the later Acheulean site of Elandsfontein (the materials are described in Chapter 2.2. below), I was able to carry out a study of the organization of different elements of Acheulean technology, as well as interrogate what these elements revealed about landscape use patterns from multiple perspectives, and in diverse temporal and geographic settings.

2.2. Materials

In this dissertation, I analysed stone artefacts from five different Acheulean assemblages. Four of these assemblages came from quasi-contemporaneous early Acheulean sites at Koobi Fora, Kenya. The last assemblage was from a late Acheulean site called Elandsfontein Cutting 10, Western Cape, South Africa. Given the age estimates of the Koobi-Fora sites to be ~1.4 Ma and Elandsfontein to be 1 Ma – 600 Ka, this thesis has a relatively wide geographic and temporal focus within the Acheulean.

2.2.1. Elandsfontein: Archaeological and experimental collections

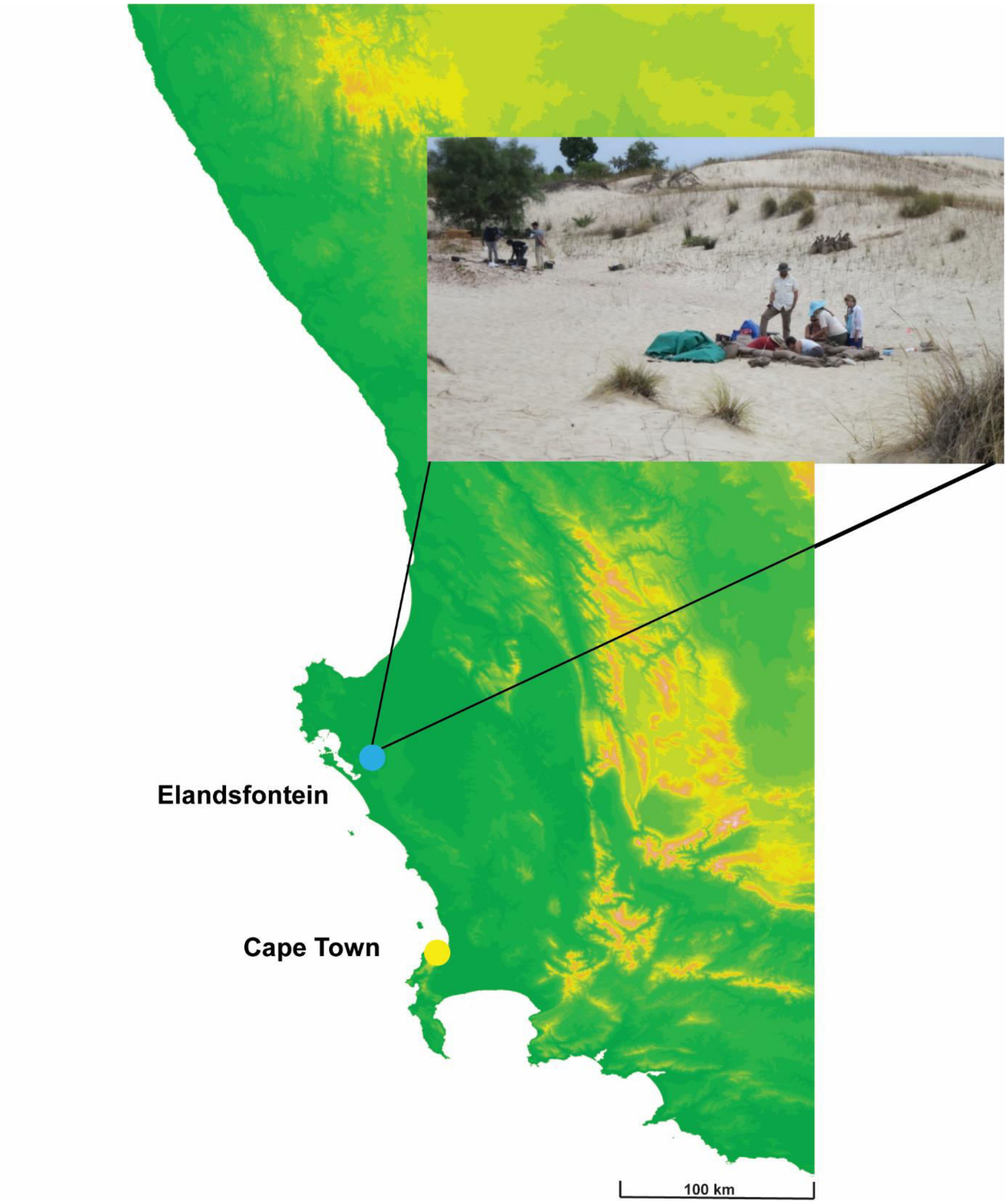

Figure 2.1. Map shows southern Africa and Elandsfontein.

Elandsfontein is a Mid-Pleistocene dunefield that has a bio-stratigraphic age determination of between 600 Ka and 1 Ma (Klein et al., 2007) (Figure 2.1). Ronald Singer was one of the more publicized early archaeologists who began exploring the Elandsfontein dunefields in the 1950s (Deacon and Deacon, 1999). Singer realized the archaeological potential of the area after witnessing the discovery of the Saldana skull in 1953. The fossil since then has been attributed to *Homo heidelbergensis,* while its discovery prompted much further investigation of this region. In the 1960s Ray Inskeep, an archaeologist from the University of Cape Town (and later Oxford University), systematically surveyed the dune field and identified the Cutting 10 locality in the south-east portion of the dune field (Singer and Wymer, 1968). All subsequent investigations, including the most recent field campaigns conducted in 2007-2014, revealed abundant and well preserved fauna as well as the ESA artefacts. However, much of this recently recovered material was situated on deflated surfaces (Braun et al., 2013). Cutting 10 remains the only locality at Elandsfontein with *in situ* archaeological and faunal materials. The site was well excavated in the 1960s, and Inskeep piece-plotted many of the finds encountered during excavation (Figure 2.2).

Archaeological assemblage

Inskeep, who was widely regarded to be a meticulous excavator, argued that Cutting 10 was a single occupation horizon where all finds had a consistent horizontal level with a sterile ferruginous sand covering the horizon (Singer and Wymer, 1968). The archaeological assemblage from Cutting 10 consisted of 208 artefacts, 66 of which were LCTs. In addition there were 29 cores and 129 flakes and flake fragments (Singer and Wymer, 1968; Archer and Braun, 2010). The most frequently used raw materials used within the Cutting 10 collection was a sub-volcanic rock referred to as quartz porphyry, silcrete, quartzite, quartz and substantially smaller amounts of hornfels. Of the 129 flakes and flake fragments, the majority had either post depositional breakages or fractures that potentially occurred during knapping (e.g. *siret* flakes). In order to measure all relevant attributes, the analysis included the 34 complete archaeological flakes larger than 2 cm in the collection.

Figure 2.2. Plan of artefacts and fossils from Elandsfontein Cutting 10 excavations. From Singer and Wymer 1968.

The investigation of the archaeological materials was conducted in conjunction with the development of the quantitative method to differentiate *façonnage* and *débitage* flakes. The method required an experimental assemblage of both *façonnage* and *débitage* flake types to develop a predictive model that would then allow a separation of archaeological flakes.

Experimental assemblage

Pierre-Jean Texier and Will Archer, two archaeologists with more than 15 years of extensive knapping experience, produced the experimental assemblage of *façonnage* and *débitage* flakes. While knapping, the two knappers had no knowledge of the intended usage, and specific archaeological application of the experimental assemblages they were generating. They therefore did not produce flakes in accordance with a specific morphological template. Quartzite and silcrete, two of the raw materials exploited at Elandsfontein Cutting 10, were used to generate the experimental collection. In producing *façonnage* experimental flakes, the knappers broadly followed the LCT production sequence previously documented for Elandsfontein Cutting 10 collection by Archer and Braun (Archer and Braun, 2010). The *façonnage* assemblage included 98 complete flakes, generated within the production of 28 LCTs. The LCTs were produced by first using a hard hammer and then switching to soft hammer on large (>10cm) side-struck flakes (flakes where the technological length is perpendicular or close to being perpendicular to the maximum length); the dominant blank-form used within the Elandsfontein Cutting 10 LCT collection (Archer and Braun, 2010). Importantly, flakes resulting from roughing out (also referred to as *ébauche)* and thinning (also referred to as *façonnage*) (Pelegrin and Texier, 2004) were combined for analytical purposes. In this way shape variation in flakes related to the activities of roughing out and subsequent shaping were both included.

Flakes related to core and flake technology were produced from the reduction of 12 (< 8cm) riverine cobbles. Rounded cortex on many of the cores and flakes from the Cutting 10 assemblage indicate that riverine cobbles were the initial form of many of the cores. To account for some of the documented variation in Oldowan like core reduction strategies (de la Torre, 2004; de la Torre and Mora, 2005; Delagnes and Roche, 2005; Braun et al., 2009b) several techniques were utilized including unifacial unidirectional, multidirectional and centripetal (discoidal) (de la Torre and Mora, 2005). Some of these reduction strategies such as discoidal and multidirectional variants have been identified within the Elandsfontein Cutting 10 collection. The experimental assemblage, the sample of 149 flakes, consisted only of whole flakes.

Flakes were considered ‘whole’ if all of the relevant variables could be measured (see Appendix 2 for a description of variables). The whole flakes were measured using a variety of calliper and digital imaging techniques (i.e. measurements that were made using the photos of flakes). In addition, whole flakes smaller than 2 cm were excluded as it has been suggested that calliper measurements are less reliable and more subjectively variable on flakes smaller than 2 cm (Fish, 1978).

2.2.2. Koobi Fora: History of site identification, geology, contextualization and excavation

The Koobi Fora Formation forms part of the Lake Turkana Basin, which belongs to the East African Rift System. The Formation consists of eight Plio-Pleistocene Members. Namely the Lonyumun, the Moiti, the Tulu Bor, the Burgi, the KBS, the Okote, the Chari, and the Silbo. The Okote Member comprises the temporal focus of this thesis, and is bracketed chronologically by the ~1.56 Ma Okote Tuff and the ~1.38 Ma Chari Tuff (Brown and McDougall, 2011). The region has been tectonically active since the Pliocene. Tectonic activity has always influenced the local geology and ecology of the Turkana Basin, the presence and absence of lakes as well as other changes in the fluvial system. As a consequence, around 1.5 Ma the Lorenyang lake, which formed at ~1.9 Ma at the obstruction of the Omo River by the Lenderit Basalt, regressed (Bruhn et al., 2011; Feibel, 2011). This lake phase was followed by the return of a less stable Omo River system, which was characterized by a series of crevasse splay events, as well as a system of small and shallow seasonal channels in the eastern part of the basin (Rogers et al., 1994). The past volcanic activities and the presence of fluvial systems that transported tephra, played a vital role in the formation of the archaeological record in the Turkana region, as the presence of tephra allows the dating of paleoanthropological and archaeological remains.

Paleoanthropological and archaeological work in Koobi Fora initiated in the 1960s with an expedition led by Richard Leakey. The team of paleoanthropologists included Kamoya Kimeu, Meave Leakey, Richard Leakey and Bernard Wood, who have all been key figures in the discovery of important fossils such as KNM-ER 1813 *H. habilis* and KNM-ER 3733 *H. erectus*. Basal Cooke focused on the faunal record, and the suids in particular. Cooke played a key role in solving the so-called KBS controversy, which revolved around the ages for the KBS tuff (Isaac and Behrensmeyer, 1997). Raymonde Bonnefille worked on ancient pollen and Anna K. Behrensmeyer, Bruce Bowen, Ian Findlater, Frank Brown, Craig Feibel, Carl Vondra, and Ian McDougall were key figures in the reconstruction of the local environments and the descriptions of the geology, and geochronology (Isaac, 1997).

Glynn Isaac, who worked at Berkley in the late 1960s, joined the project to head the archaeological research. Isaac and his graduate students including Jack Harris, Henry Bunn, Ellen Kroll, Kathy Schick, Jeanne Sept, Nick Toth and Nicola Stern discovered and mapped over 60 archaeological localities in the KBS and Okote Members, and excavated 20 of them between 1970s and 1990s (Isaac, 1997).

Jack Harris, excavated a group of sites dated to ~1.5 Ma in the Karari Ridge region in Koobi Fora, and discovered a new technological industry that was named the Karari Industry (Harris and Isaac, 1976; Harris, 1978). Most importantly for this thesis were the excavations and the surveys of the early Acheulean sites by Jack Harris, Karin Liljestrand, Paula Villa, Zefe Kaufulu and Jeanne Sept in the 1970s.

These early Acheulean sites analysed as part of this dissertation work, namely, the sites of FxJj65, FxJj63, FxJj37 and FxJj21 which are quasi-contemporaneous and represent the best-documented sites attributed to the early Acheulean from the Koobi Fora Formation (Isaac and Harris, 1997) (Figure 2.3). The limited chronological spread of these assemblages provided the opportunity to study how artefact shape, size, and technology varied between a set of assemblages which were probably produced and used under a comparable landscape scale frameworks of resources (Brown and Feibel, 1985).

Importantly, a single raw material (fine-grained tholeiitic basalt) was used to produce all of the studied assemblages (Braun et al., 2009a). Raw material form variability is a known driver of lithic variability in general, and is known to impact LCT morphological variability (Ashton and McNabb, 1994; White, 1995, 1998). The limited nature of raw material variation within the dataset enabled the drawing of inferences about artefact forms that were less contingent upon the properties of different stones. Although a single raw-material was used, differences in raw material availability – i.e. the variable distances of sites from available sources of raw material – certainly may have influenced LCT variability at Koobi Fora.

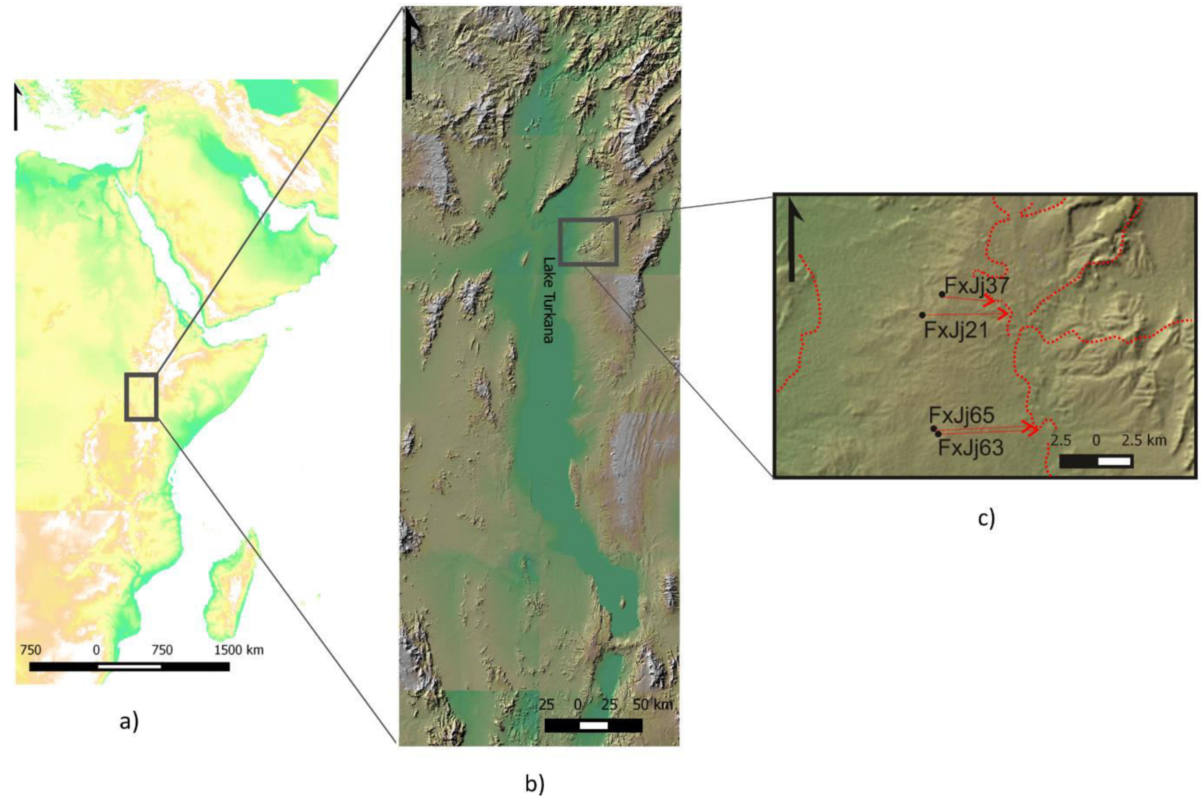

Figure 2.3. a) Map of eastern Africa; b) Lake Turkana; c) Image of Koobi Fora, showing the Karari Escarpment and the four sites: FxJj65, FxJj63, FxJj21 and FxJj37. The red line indicates the borders of the basalt outcrop.

Archaeological assemblages

The first site, FxJj65, was documented initially by Jack Harris in 1978 (E 36.424/ N 4.078 WGS 84). In two excavation seasons from 2010 to-2011, I directed excavations that recovered 675 *in situ* early Acheulean artefacts, as well as 484 artefacts from directly associated yet deflated contexts at FxJj65. The edges of the *in situ* FxJj65 artefacts show little macroscopic evidence of post-depositional movement (~10% of the artefacts have signs of some post-depositional damage). Volcanic tephra found within the stratigraphic section at FxJj65, as well as in adjacent stratigraphic sections, are similar in chemical composition to the tephra recovered at the site of FxJj63. Previous geochronological studies of this tephra estimate the age to be ~1.41 Ma (Brown et al., 2006). As such, FxJj65 fits within the upper Okote Member.

The site of FxJj63 is located approximately 500 m from FxJj65 (E 36.424/N 4.086). Jack Harris excavated this locality in 1978 (Harris and Isaac, 1997). The excavations yielded ~1000 *in situ* artefacts, in addition to >1000 finds from directly associated deflated contexts. Fluvial post-depositional processes affected the distribution of artefacts at the FxJj63 site (Harris and Isaac, 1997). Some of the smallest fraction of specimens are missing from the assemblage. This said the finds are unlikely to have been transported substantial distances since original deposition. Relatively few artefact edges have obvious macroscopic evidence of post-depositional damage (11.9% of the artefacts have either damaged or rolled edges). Refits between a core and an LCT flake blank provided further support that artefacts were only minimally transported. Geochemical analysis of the tuff identified at this site (Brown et al., 2006) situates it in the upper Okote Member. As such, the site is largely contemporaneous with FxJj65.

The site of FxJj37 is located approximately 8.7 km northeast of FxJj65 and FxJj63 sites (coordinates from Harris and Isaac: E 36.426/N4.161). Jack Harris and Karin Liljestrand identified, and subsequently excavated the site in a 1978-1979 field season. Through a detailed correlation of geological sections, both Harris and Isaac (1997) and Isaac and Behrensmeyer (1997) described the site as being situated within the upper part of the Okote Member. The excavation of this locality produced 603 *in situ* artefacts in addition to >200 finds from a likely associated deflated surface (Liljestrand, 1980; Harris and Isaac, 1997). The artefacts within this excavation were suggested to have preferential orientations. As such it is possible that fluvial action impacted the deposition of these materials. The edges of approximately 12.5% of the recovered specimens indicate evidence of rounding, possibly as a result of exposure to fluvial abrasion (Liljestrand, 1980; Kaufulu, 1987; Harris and Isaac, 1997). However, based on the minimal size of the paleo-channel and the low frequency of abraded specimens, the initial description concluded that - although fluvial processes were potentially responsible for modifying the overall spatial distribution of the finds - the artefact concentration was the product of a single depositional event attributable to hominin behaviour.

FxJj21 is situated approximately 8 km North of FxJj65 and FxJj63 (E 36.414/N 4.15). FxJj21 was first identified in 1977 (Harris and Isaac, 1997). Full stratigraphic information is not currently known for FxJj21 as the majority of the finds were recovered from surface contexts. Adjacent sediments correlate to the Upper Okote Member (Harris and Isaac, 1997:112). A volcanic ash identified nearby the major concentration of artefacts at FxJj21 is geochemically similar to the ash recovered at FxJj63. Here we assume that FxJj21 has a minimum age of 1.41 Ma, still, the exact age of FxJj21 is yet to be established (see geochemical analyses below). FxJj21 represents a deflated surface with 108 artefacts scattered within a 15 m^2 area. Since no artefacts were unequivocally recovered *in situ,* we have opted to include only certain elements of this assemblage in our study. We include specimens that conform to the definition of early Acheulean LCTs in the detailed technological analysis. Since all of this assemblage was recovered from the surface there is obvious evidence of weathering on many specimens. Despite this, more than half of the assemblage (62.5%) has edges with no macroscopic evidence of edge rounding.

Descriptive analyses were undertaken on the entire collections of LCTs from FxJj65, FxJj63, FxJj37, and FxJj21 which are located at the National Museum of Kenya (n=277). 3DGM analyses, however, were only undertaken on complete, unbroken specimens with clearly defined tips and bases (n=214). In other words, specimens that had fractures that modified their original sizes and morphologies were excluded from the 3DGM analysis. In addition, LCTs which did not have clearly definable elongation axes (technological length and width) – thus making them difficult to orient accurately – were not included in the 3DGM analysis. There is an unavoidable unequal distribution of numbers of specimens between sites. Nevertheless, this imbalance does not violate any assumptions regarding general linear model stability (Quinn and Keough, 2002), and in fact led to some important archaeological inferences regarding the differing site functions of these localities (see appendix 2)

Experimental assemblages

To facilitate our interpretation of patterns of artefact reduction stages in the archaeological data, and to interpolate stages that might be missing, an experimental collection of LCTs was generated. The experimental LCTs were produced within the published parameters of early Acheulean technological strategies (de la Torre and Mora, 2005; de la Torre, 2011; Beyene et al., 2013). For example, no repetitive bifacial alternations between knapping surfaces were undertaken, which is a typical characteristic of classic later Acheulean bifaces, yet is far less common in early Acheulean assemblages (de la Torre et al., 2008). In all experimental reduction sequences, the majority of removals were non-invasive, and focused on a single knapping surface that in most cases constituted the dorsal surface of the original flake blank.

Each experimental LCT production trajectory was divided into four categories that were determined solely by the number of flakes removed in any given experiment. This resulted in an experimental dataset of 18 specimens. At each of these stages, experimental LCTs were measured and scanned with the Next Engine three dimensional surface scanner for subsequent 3DGM analysis.

CHAPTER 3. RESULTS AND DISCUSSION

3.1. Quantitative models for characterizing Acheulean technological behaviours

3.1.1. A discriminant model for characterizing Early Stone Age *façonnage* and *débitage* products

A method to differentiate shaping and non-shaping flakes was mentioned above and was presented in the paper Presnyakova, et al. 2015 (Appendix 1). This method, and its predictive capacity for the archaeological record, relies on the demonstration that Acheulean bifacial shaping and Oldowan like core reduction strategies result in flakes with different morphologies (see Chapter 2.1.1.).

A critical part of building this model was developing new and selecting existing variables, based on previous experimental research, that would be informative in characterizing flake shape. The variables included external platform angle (hereafter "EPA'"), platform depth, the thickness evenness coefficient and a new curvature measure, as well as the interactions between some of these variables (Figure 3.1).

EPA, a parameter that is directly controlled by the knapper, was the angle measured between the striking platform surface and dorsal surface of a flake, directly behind the point of percussion (Dibble and Whittaker, 1981; Dibble and Pelcin, 1995; Dibble, 1997; Pelcin, 1997a; Dibble and Rezek, 2009; Lin et al., 2013; Magnani et al., 2014).

Platform depth was the variable that measured the distance from the point of percussion to the point of intersection between the platform surface and the dorsal surface of the flake (Dibble, 1997). In order to control for allometry this variable - platform depth - was standardized by dividing it by the geometric mean of all size related variables such as length, width, thickness and platform width (Cramon-Taubadel and Lycett, 2008). This size adjustment enabled the documentation of shape differences associated with platform variability that are not directly related to size (Jungers et al., 1995).

The thickness evenness coefficient captured variation in flake thickness along the flake technological length axis. Thickness was measured at the positions of 25%, 50%, and 75% of the technological length, and the standard deviation of these three measures was then calculated. Low values indicated that thickness measurements did not vary greatly along the technological axis of a given flake whereas high values indicated substantial variation in thickness along the technological axis. High values of standard deviation would be expected to characterize flakes where the volume was concentrated at one point in the flake (e.g. bulb of percussion).

The last variable, flake curvature, was an angle measurement that was measured on flakes when they were oriented in profile view. Several studies have suggested that core surface maintenance contingently affects the shape of the flakes removed from these cores (Pelcin, 1997b; Rezek et al., 2011; Magnani et al., 2014). The curvature on flakes was calculated on images of flake profiles using Image J 1.43u software.

The above-described variables were used as test predictors in two multivariate statistical models built to distinguish the forms of flakes associated with different strategies. In addition, raw material type was included as a control predictor. Finally, group membership of flakes, as resulting either from *façonnage* (i.e. associated with LCT manufacture/maintenance) or *débitage*, was the response variable in the formulation of the model based on experimental data.

The first multivariate statistical technique used in the study was discriminant function analysis (hereafter ‘DFA’). This technique constructs linear functions which maximize between group variance in pre-existing groups (Johnson and Wichern, 2002; Mundry and Sommer, 2007). Once the discriminant function is developed, using cases of known group classification, one can reclassify the individual observations using a leave-one-out approach known as cross-validation. In this way one can develop a probability of group affiliation for each individual case i.e. each flake (Johnson and Wichern, 2002). A key utility of discriminant function analysis, and in fact any multivariate predictive model, is that it ultimately enables the classification of data that were not used to build the discriminant model, which is where the archaeological application becomes relevant.

In this study, the model was built using the experimental data set (described in Chapter 2.2.1.), wherein the strategies used to produce each flake were known. This was followed by the classification of a group of experimental flakes that were not

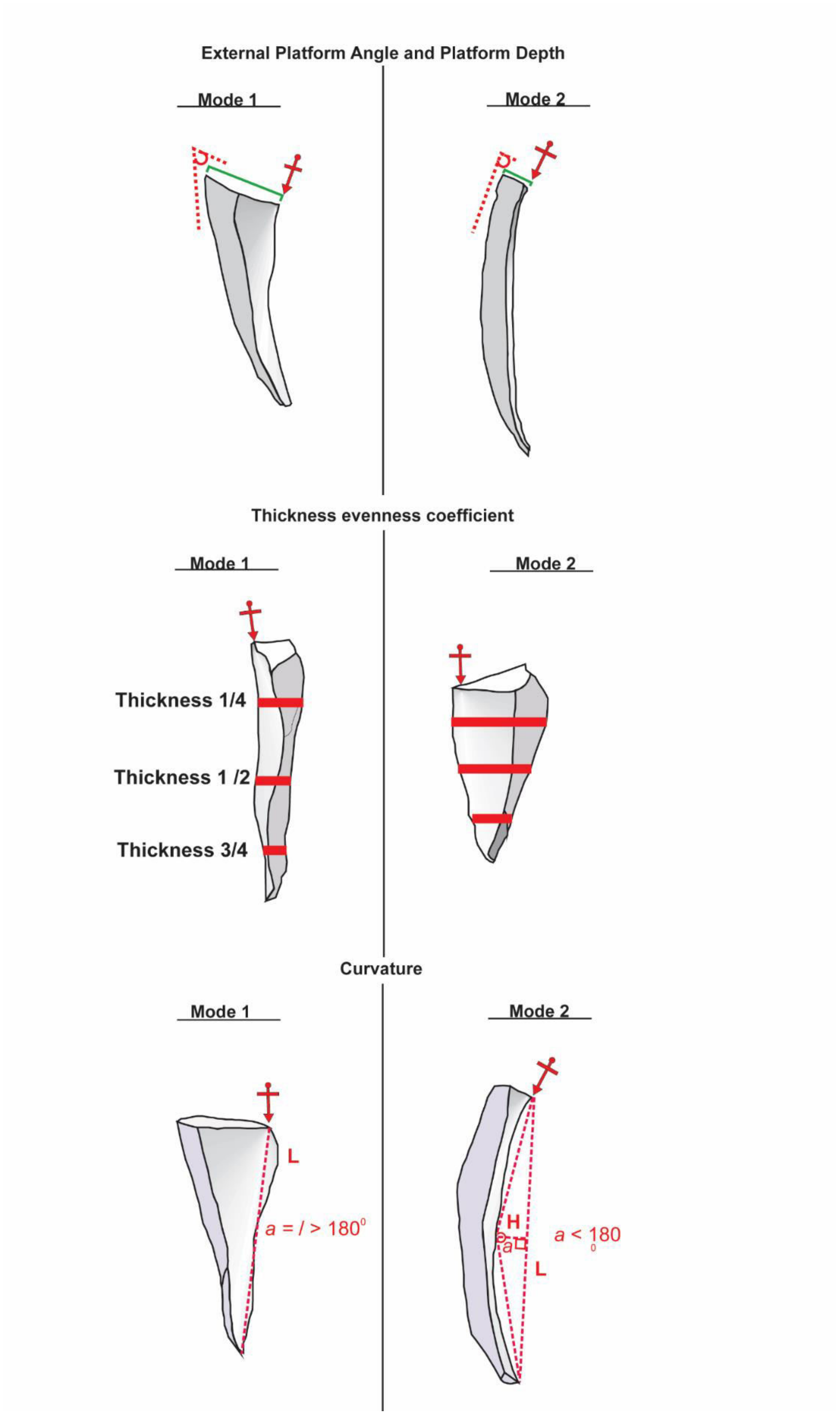

Figure 3.1. **External platform angle and platform depth**: Dashed line represents EPA, solid line represents platform depth and arrows are points of percussion; **Thickness evenness coefficient:** Arrows show points of percussion, whereas solid lines represent places on a flake where thickness was measured; **Curvature:** Arrows represent points of percussion, dashed lines are the outlines of right triangles composed from the technological length and the height measurements.

used to build the initial model (the test data), to assess the number of flakes classified correctly. This alternative means of validating the model served to verify the discriminant function.

Finally, archaeological flakes – where of course we cannot be sure what strategies were used to produce them - were classified using the model. In this way the discriminant function analysis produces a probability of association value that estimates the likelihood of the association of each flake with a given production strategy.

In addition to DFA the data were analysed using the Generalized Linear Model with a binomial error structure and the logit link function (Dobson, 2002). The same set of predictors used in the DFA were included in the GLM model. Additionally, several interactions, one between platform depth and EPA, another between platform depth and thickness evenness, were included in the analysis. The reason for fitting an additional model, is that GLMs provide far more accessible information about what is driving the effects and interpreting the predictive power of the model, that is not as easily obtainable from the output of a DFA. Due to the uneven distribution of cortical and non-cortical flakes between the *façonnage* and *débitage* flakes, cortex presence was included as a control predictor into the GLM. The model was fitted in R (R Core Team, 2017), using the “glm” function.

The discriminant function analysis resulted in an astounding 87.4% success rate in experimental flake classification. The subsequent analysis with jackknife re-sampling, a cross validation method of leaving one observation out (Kovarovic et al., 2011), resulted in an equivalent percentage of correctly classified cases.

A likelihood ratio test comparing the null and the full Generalized Linear Models was also highly significant (χ^2=225, df=7, P< 0.001). The reduced model that did not include interactions revealed that curvature, thickness evenness, platform depth and EPA were all significant predictors of technological group affiliation. The interaction between thickness evenness and platform depth was significant according to the likelihood ratio test comparing the reduced (no interaction) and full models (χ^2=239, df=1, P< 0.01). Importantly, the significance of the interaction implies that at greater platform depths, thickness evenness had a greater impact on the separation of whole flakes in the *façonnage* or *débitage* groups.

The experimental linear discriminant model in its predictive capacity enabled the classification of 68% of flakes from Elandsfontein Cutting 10 as *débitage* flakes (in the paper we referred to them as Mode 1 flakes) and 32% as *façonnage* flakes (or Mode 2). Most Mode 2 flakes were made on silcrete, and the majority of the Elandsfontein Cutting 10 archaeological flakes (79%) were too made on silcrete. This contrasted with 62.5% of the LCTs that were made on quartz porphyry, 10.5% on quartz, and only 27% of LCTs were made on silcrete. The absence of quartz porphyry flakes in the assemblage suggested at the outset that LCTs made on these raw materials were manufactured and maintained away from the site. In contrast, based on (1) the absence of LCT blanks or preforms, and (2) the presence of Mode 2 silcrete flakes, we proposed that silcrete LCTs were manufactured away from Cutting 10, but underwent some maintenance at the Cutting 10 locality.

Although researchers like Andrew Bradbury, Philip Carr and Michael Shott have more recently been developing methods for differentiating flake types within North-American archaeological contexts (Shott, 1996; Bradbury, 1998; Carr and Bradbury, 2011a), this thesis presents the first quantitative model to differentiate *débitage* and *façonnage* flakes within an ESA context, or within any African archaeological context.

This modelling approach is significant, as numerous sites have been classified as Acheulean, but their attributions remain contentious due to a lack of traditional characteristics, namely, absence of classical LCTs. For example, as LCTs are often made on flake blanks it has been suggested that the presence of systematic large flake production may be diagnostic criteria of the Acheulean technocomplex in contexts where LCTs were not present (Ludwig and Harris, 1998; Goren-Inbar and Sharon, 2006). A number of Pleistocene sites have consequently been identified as being representative of the Acheulean industry solely based on evidence for large flake production. Some examples include FC West, Olduvai Gorge (de la Torre and Mora, 2005), Kokiselei 4, West Turkana (Roche et al., 2003), and FxJj63 in Koobi Fora (Ludwig and Harris, 1998).

Additional examples are known from younger Middle Pleistocene contexts such as the Nadung'a 4 locality in West Turkana, which is a Middle Pleistocene site dated to around 700 Ka. Artefact assemblages at Nadung'a 4 contain denticulates and notches, but no LCTs have been identified (Delagnes et al., 2006). Likewise, layers V-5 and V-6 at Gesher Benot Ya'aqov, Israel contain no LCTs but were assigned to the Acheulean through qualitative characterization of technological aspects of flake collections (Goren-Inbar and Sharon, 2006). The quantitative method of identifying *façonnage* flakes presented here widens the spectrum of assemblage characteristics through which *shaping* can accurately be identified (i.e. within a known error range) in an Acheulean context.

A prominent suggestion in the literature is that the emergence of bifacial technology coincided with the demise of core and flake technology (Foley and Lahr, 1997, 2003). This linear trajectory of technological evolution is challenged by certain Middle Pleistocene sites like the later site of Bodo (> 600k) that exhibits only simple core and flake technologies without any evidence of LCT manufacture (Clark et al., 1994; Schick and Clark, 2003). Additional challenges are present at sites such as Olorgesailie, Kenya (Potts et al., 1999), Peninj, Tanzania (de la Torre et al., 2008), Koobi Fora, Kenya (Harris and Isaac, 1997) and Gadeb, Ethiopia (de la Torre, 2011), where instances of clear core and flake *débitage* are present in association with LCT manufacture. An important characteristic that these examples share is that multiple technological strategies were practised at the same site.

This thesis documented relatively simple core and flake products that were expediently manufactured at the site of Elandsfontein. These flake production systems co-occurred along with the curated LCTs that entered the site in already finished form. Although identifying and differentiating cores and LCTs themselves is straightforward, differentiating bifacial flakes from non-bifacial elements at sites without the cores is far less trivial, even for an experienced lithic analyst (for a different view see (Roche and Lefevre, 1988; Boëda et al., 1990; Anikovich et al., 1998; Soriano et al., 2015). The quantitative predictive model proposed here not only assists in sorting *débitage* and *façonnage* products with measures of probability of association and error, but also offers new ways to decipher and quantify activities that have taken place at a site and to understand aspects of Acheulean technological organization in a landscape context (Bradbury and Carr, 1999; Carr and Bradbury, 2011b).

3.1.2. A new 3DGM model for characterizing LCTs and its application to an early Acheulean context

The 3DGM methodology described in the Presnyakova et al. 2018 paper (Appendix 2) presents the first holistic quantification of artefact shape in an early Acheulean context. This study faced three main challenges at the outset (see Chapter 2.1.1. for more details). Namely, 1) how to orient specimens reliably (Appendix 3 presents a discussion about potential issues caused by misorienting specimens during the 3DGM), 2) how and where to place fixed initial landmarks and equidistantly spread them along bifacial edges; and 3) how to warp landmarks on the artefact surfaces using a single template specimen. In a highly irregular assemblage of specimens, these comprised considerable hurdles of this study.

At the outset archaeological and experimental LCTs (materials described in Chapter 2.2.2.) were scanned with a Next Engine surface scanner. Meshes were subsequently cleaned, trimmed and fused. A recent study by Archer and Presnyakova demonstrated how incorrect orientation of LCTs, as well as small errors in the placement of landmarks, can have drastic effects on the documented spectrum of variability in an assemblage (Archer and Presnyakova, 2019). To avoid these serious pitfalls of incorrect orientation, the LCT meshes were oriented in two orthogonal planes, namely, 1) the axis linking the tip and base (the technological length axis), and 2) the plane orthogonal to the axis of the tip and the base. The second orientation plane 2) was therefore perpendicular to, and intersected the two LCT faces. Most critically, the second orientation step 2) ensured that the most convex surface of each biface always faced the same direction.

Initial landmarks were manually placed on the LCT tips, bases and the lateral edges using the Landmark v3 software. The 3D coordinates of the tip and the base constituted the only geometrically correspondent individual landmarks at the outset, on each LCT. Forty semi-landmarks were then manually placed on each of the two edges of each LCT. The landmarks on each edge were then equidistantly spaced in three-dimensions using the “digit.curve” function in the Geomorph package in R (Adams and Otárola-Castillo, 2013).

In the past there have been GM studies where scientists positioned landmarks only on artefact edges and not on artefact surfaces (Buchanan et al., 2012; González-

José and Charlin, 2012; de Azevedo et al., 2014). These studies by and large focussed on Holocene projectile points that were bifacially symmetrical, with evenly distributed thickness on both sides of an artefact. In other words there was minimal bifacial variation, which suggests that using only edge landmarks in these contexts was reasonable. Surface landmarks require the laborious computationally intensive technique of projecting landmarks from a chosen template specimen to the rest of the specimens in a collection. In contrast to Holocene projectiles, thickness in early Acheulean LCTs tends to vary greatly within and between specimens. So, in LCTs, without the incorporation of surface landmarks much information about artefact morphology would have been lost.

Several methods, such as thin-plate spline ('TPS'), are available for warping semi-landmarks from template to target specimens. However, these original methods were designed for relatively standardized shapes and single-layered meshes. Early Acheulean LCTs are complex forms, with multiple discrete surfaces in some cases. In this sense the probability for target landmarks to "migrate" from one surface to another is reasonably high which, if this happened, would be a major problem for the analysis. I therefore used a combination of various functions in the mesheR package, which relies on Gaussian Process and multiple iterations of elastic registration to warp the template onto a target. Ultimately I was able to make this work for all specimens in the studied Koobi Fora assemblages. The Gaussian Process approach allows one to capture a target shape by smoothing a model over it and computing a weighted average from the model estimation at each iteration (Schlager, 2017).

The first step for the surface landmarks was placing landmarks manually on the two surfaces of a randomly chosen single template LCT specimen; that step produced three hundred and twenty landmarks (160 on each LCT face). The template configuration of landmarks was then digitally deformed onto the surfaces of each of the other LCT meshes in the collection. It worth mentioning that changing the template LCT did not change the results. This process resulted in a configuration of 362 geometrically correspondent landmarks for each specimen.

All LCT landmark configurations were then adjusted using Procrustes superimposition, which standardizes size, orientation, and position amongst specimens (Rohlf and Slice, 1990).

My hope is that other researchers may adopt the 3DGM model presented here to apply to other early Acheulean collections with LCTs for comparative purposes. Technological advancements in 3D data capture, with 3D scans becoming increasingly affordable and fast, the expansion of automated landmarking and computation techniques, and the growing availability of machine learning algorithms, should make these types of quantitative analyses far easier and more accessible to a wider range of researchers in the future.

3.2. The behavioural implications of LCT variability

Several alternating hypotheses were advanced in Presnyakova et al. (2018) (Appendix 2), regarding the underpinnings of LCT variability between the sites of FxJj65, FxJj63, FxJj37 and FxJj21. The null hypothesis was that no variability existed between the sites, with the second and alternative hypothesis being that variability existed and was underpinned by artefact reduction intensity. The third hypothesis was that variability was underpinned by the presence of two or more technological traditions of making LCTs that were practised by occupants across these sites (socially learned manufacturing traditions). I explain the reasoning behind the hierarchy of these hypotheses elsewhere (see discussion of Isaac's Method of Residuals Chapter 2.1.1.).

3.2.1. Summary of quantitative findings and behavioural implications

At first glance the LCTs from the four sites exhibited statistically significant differences in the metric parameters of mass (one-way ANOVA, $p<0.001$ degrees of freedom [df]=2), length (one-way ANOVA, $p<0.001$ df=3), width (one-way ANOVA $p<0.001$ df=3), and scar count (one-way ANOVA, $p<0.001$ df=3) (Figure 3.2). Large cutting tools at FxJj65 and FxJj63 appeared to be longer, wider and heavier compared with LCTs from the sites of FxJj37 and FxJj21. LCTs from the sites of FxJj21 and FxJj37, had more removals per artefact, indicating that they were more intensively reduced in comparison to LCTs from FxJj65 and Fxjj63. Large cutting tools from FxJj37 and FxJj21 were mostly non-cortical, falling into either the 1–10% category or the 0% category, while both FxJj65 and FxJj63 had highly variable distributions of cortex.

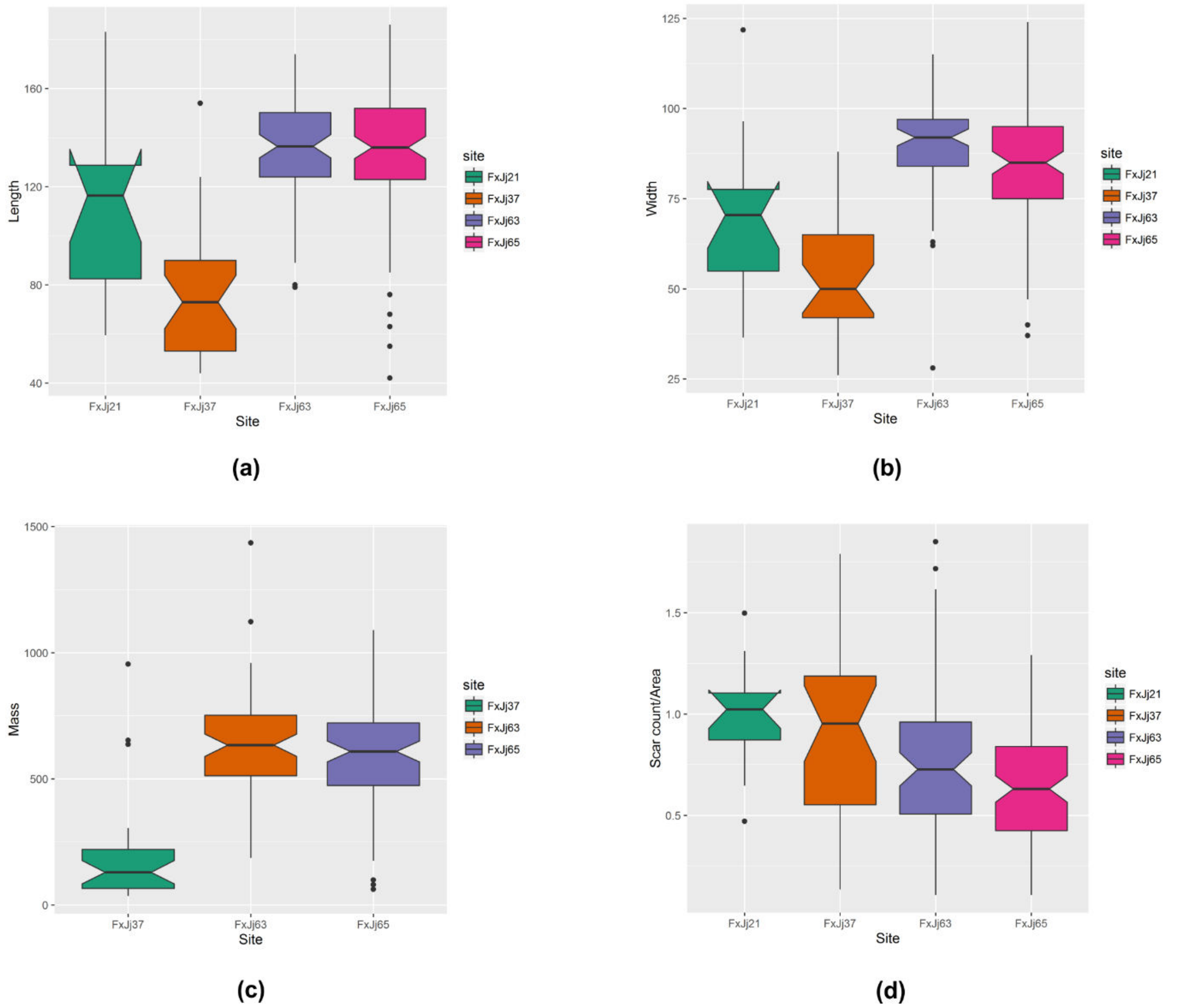

Figure 3.2. The metric parameters of LCTs including Length-mm (a), Width-mm (b), Mass-gr (c) and Scar counts divided by area (d). The line of the notched box plot shows the median, while the notch represents the 95% Confidence Interval. The plot was made using the ggplot2 R package (Wickham, 2009).

The major axes of shape variation in the archaeological LCT assemblages were visualized with principal components analysis (hereafter ‘PCA’), and a bivariate plot of principal component (PC) 1 and 2 scores. Maximum and minimum theoretical LCT shape extremes were also calculated (Figure 3.3). The differences in mean LCT shape between the archaeological sites were investigated using multivariate analysis of variance (MANOVA, Type II) on the first 12 PCs of LCT shape variation. This analysis was undertaken to test whether there were statistically significant differences between the mean LCT shapes from the four archaeological sites.

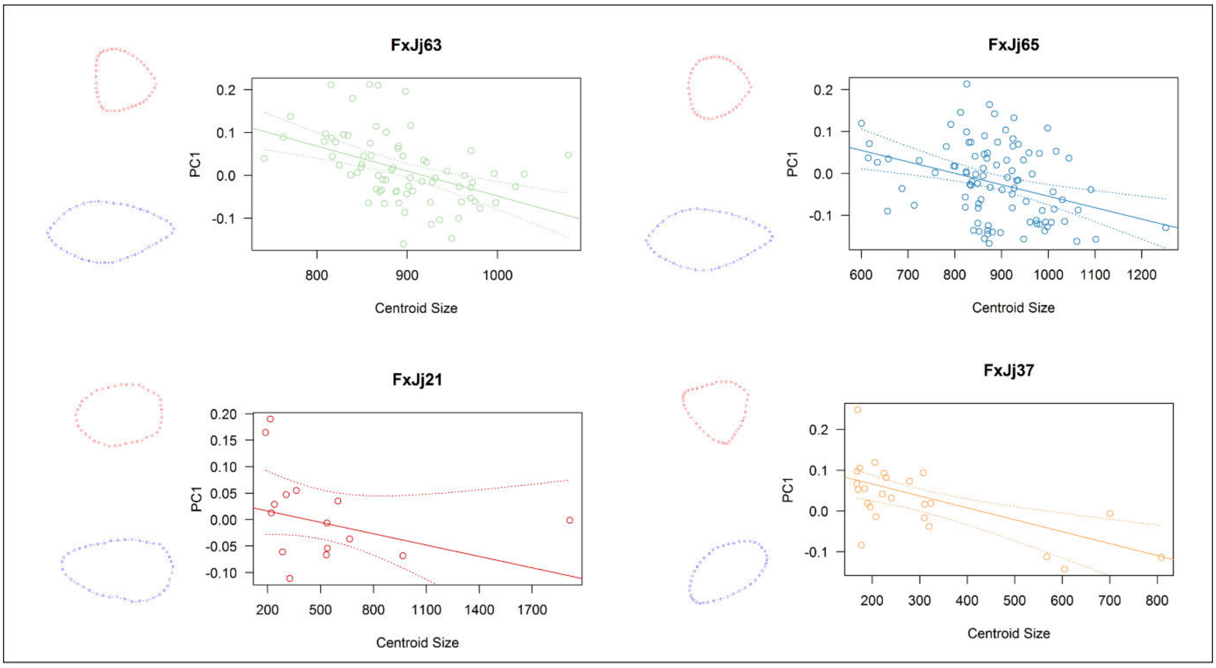

Figure 3.3. Principal component 1 of shape variation versus centroid size for each archaeological site. The dotted lines show 95% confidence intervals of the model (solid line).

The results of applying 3DGM and conducting PCA revealed that PC1 explained 20% of the variance and PC2 explained 14% of the variance among the Koobi Fora sites. The MANOVA, using site affiliation as the sole predictor, showed that although there was substantial overlap on PCs 1 and 2, statistically significant differences existed in LCT shapes between the four sites ($F=2.669$, $p<0.001$ df=3). The data therefore suggested that the structure of LCT variance within each of the sites was largely the same, but that the mean shape of LCTs was significantly different between the sites. The results of the 3DGM, as well as the conventional attribute analyses, allowed disregarding the null hypothesis that no variation existed in the LCT sample from Koobi Fora.

To further investigate the effects of hominin behaviours associated with tool reduction and LCT allometry (shape related to size), a set of independent variables were also measured (size, scar count, edge angle coefficient of variation [CV], cortex coverage, and number of knapping platforms). These independent variables were selected under a set of predictions – laid out in Appendix 2 - that they would track LCT reduction. The most obvious experimental prediction is that, because knapping is inherently reductive, artefact size would decrease with reduction. In addition of the quantity of observed dorsal cortex would also decrease, while the counts of surface scars (adjusted for artefact volume) and knapping platforms would increase with reduction. Further, due to the nature of bifacial production we predicted that LCT edge angles would become increasingly variable, as measured along the edge of the entire LCT.

First, the ability of these independent variables to predict LCT shape and size was modelled in the experimental collection. The effects of the independent variables on LCT shape were examined using multiple regression, primarily to document which components of LCT shape were driven by patterns of LCT manufacture and maintenance.

As the experimental LCTs were associated with known stages of reduction, it allowed me to explore both a) the general changes in size and shape associated with LCT reduction, as well as b) the combination of independent variables which best explain these changes. In this experimental regression model, the degree of LCT reduction (as approximated by number of removals) (Shipton and Clarkson, 2015) comprised the response variable while edge angle (CV), size (mass), cortex and knapping platforms comprised the independent predictors.

The r^2 of the multiple regression model was high (0.91). Both edge angle (CV) and mass were highly significant predictors of LCT reduction in the experimental collection. Surprisingly though, neither a) cortex coverage nor b) number of knapping platforms were significant predictors of the extent of experimental LCT reduction. These two variables were therefore not included in the model applied to develop predictions for the archaeological data.

As edge angle (CV) was highly significant, this prompted me to investigate the interaction of this variable with the archaeological shape data, to assess which aspects of archaeological shape were likely to be underpinned by reduction. The only differing feature of the archaeological model, in comparison with the experimental model, was that it included archaeological site – i.e. the site from which each LCT derived – as a control predictor.

In the archaeological analyses, the effects of edge angle (CV) and centroid size on archaeological LCT shape were highly significant ($F=10.54$ $p<0.001$, $df=5$). The multiple regression model assessing the effects of reduction on archaeological LCT shape, implied that the major axis of archaeological LCT shape variation was underpinned by the influence of hominin behaviours associated with LCT reduction, and that the differences in LCT shapes between the sites were likely associated with tool manufacture and maintenance behaviours.

3.2.2. Trajectories of LCT life-history at Koobi Fora

Prior to this study, little was known about the trajectory of shape changes early Acheulean LCTs underwent, nor whether LCT life histories were spatially structured on a landscape scale. The analysis of how LCT shape changed as reduction was progressing revealed three recognizable stages of reduction. Although not discrete, these stages were a) marginally reduced LCTs, with oval shapes which closely resemble original blank forms, b) elongated, extensively reduced specimens and c) discoidally shaped, exhaustively reduced specimens where the biface tips have been longitudinally maintained or resharpened.

In Koobi Fora the reduction trajectory of LCTs seems to resemble broadly the model proposed by Shannon McPherron (1994) for the later Acheulean sites of Cagny-la Garenne and Gouzeaucourt. McPherron's idea was that what at the outset looked like substantially varying LCT morphologies actually represented stages in a single reduction continuum, where 'Pointed' LCT shapes graded into 'Ovate' (McPherron, 1999). Archer and Braun (2010) observed similar patterns to the McPherron continuum of LCT shape at the South African site of Elandsfontein Cutting 10, which identifies the possibility that this pattern may be a 'Pan-Acheulean' phenomenon.

Although pointed and ovate forms both occurred in almost all of the Koobi Fora collections, the shape changes associated with reduction appeared to be similar but slightly more complex than the spectrum described by McPherron (1994, 1999). For instance, at the sites of FxJj65 and FxJj63, shape variance was characterized by the shift from round and large LCTs resembling their original flake blanks to more elongated and narrow forms. However, the tail of this reduction trajectory, probably representing tool maintenance, was only represented at the site of FxJj65 where it was characterized by small and ovate or discoidal looking LCTs where the tip lengths of the LCTs have been reduced further through longitudinal resharpening. In this way, McPherron's reduction model explained the very late stages in LCT life histories at these Koobi Fora sites, but does not explain the early stages of manufacture, and therefore does not tell the whole story. The model of early Acheulean LCT life histories that I propose in this thesis is offered as a hypothesis to be further refined and continually tested in future research.

3.2.3. Diachronic variation versus synchronic landscape usage in the Early Acheulean

Labels such as 'early' and 'late' Acheulean are suggestive of the presence of chronological change of artefact forms between the earlier and the later variants. This is further reflected in the notion that archaic or crude earlier Acheulean biface industries evolved into later more 'refined' and symmetrical bifacial forms (Beyene et al., 1997, 2013; de la Torre et al., 2008; Lepre et al., 2011; Stout, 2011). Although it might be so, this study shows that when multiple contemporaneous early Acheulean localities are analysed together, and a relatively broad window on LCT variability is documented, a complex and variable set of LCT forms are revealed to exist at a very similar point in time. Some look like typically crude early LCTs, yet others are more symmetrical and refined, and would get lost in later Acheulean assemblages. These results do not imply that technology was not changing through time. Rather these results imply that a more nuanced study of diachronic change may be warranted, that incorporates the spectrum of synchronous variability that existed at specific times in the Acheulean, such as is documented here for the early Acheulean.

In order to investigate the third hypothesis of whether LCT variability between the sites at Koobi Fora was related to variables other than reduction, a novel quantitative adjustment was applied to the data. Namely, the LCT landmark configurations were adjusted to minimize the effects of reduction on LCT shape. Here, the protocol described by Archer and colleagues (2016) was followed. The first step of the protocol was fitting a linear model that regressed the Procrustes shape coordinates of the archaeological LCTs on both centroid size and edge angle (CV). As I already explained in the preceding paragraphs, centroid size and edge angle (CV) predict the extent of reduction in LCTs. The second step was to examine the residual variance that edge angle (CV) and centroid size did not explain. In this way, the residuals were treated as the aspects of shape variation remaining once the effects of tool reduction were minimized.

A MANOVA was then conducted on the first 12 components of adjusted LCT shape. The results of the MANOVA suggested that once the effects of reduction on shape variance have been removed, the range of LCTs in each of the archaeological sites overlapped entirely ($F=1.327$, $p=0.10$, $df=3$) i.e. there were no differences between sites. The third hypothesis therefore could not be supported. The 3DGM analyses show that the LCT forms range from typically crude and asymmetrical early Acheulean LCTs to relatively refined and symmetrical pieces, all of which fall on a single early Acheulean reduction trajectory. The trajectory remained much the same for all archaeological sites, yet different aspects of this trajectory were represented at the different sites. This study argues for a uniform technological tradition of stone tool manufacture and maintenance across all of the early Acheulean sites at Koobi Fora.

What prompted this uniform Acheulean technological tradition? What was driving spatially dispersed groups of Koobi Fora hominins at 1.4 Ma to manufacture and maintain their stone tools using the same knapping processes? One possible explanation is that hominins were transmitting the knowledge of LCT manufacturing patterns between one another. An alternative scenario is that different groups or individuals independently invented or converged on the same technological solutions. What data would support or argue against either scenario?

3.2.4. LCT variability and knowledge transmission mechanisms

The issue of whether, to what degree, and via what mechanisms knowledge transmission regarding technological know-how was transmitted in the Acheulean, and more broadly in the ESA, is a contentious topic (see Chapter 1.1. for the discussion). There are researchers who argue that certain aspects of both the Oldowan and the Acheulean are suggestive of the operation of high-fidelity social learning mechanisms in these contexts (e.g Gowlett, 1984; Wynn, 1985; Shipton, 2010 among others). Other researchers argue that cumulative culture was clearly present within the ESA, yet emerged only in the later part of the Acheulean (~0.7 Ma) (Stout, 2011; Stout and Hecht, 2017). Yet others propose that there is little convincing evidence supporting high-fidelity transmission mechanisms in the ESA (Tennie et al., 2016). While knowledge gained from studying the early Acheulean at

Koobi Fora is not sufficient to reject or promote any of these three hypotheses, ше has enabled me to draw out some relevant findings, and lay out a set of predictions for future investigation.

The knapping technology that we see across the four archaeological sites at Koobi Fora - located at a maximum distance of 10 km away from one another - was possibly less likely to have been independently reinvented by hominins in a short period of time (+/- 100 Ka). One parsimonious explanation is that social learning mechanisms of knowledge transmission were involved. Importantly, social learning mechanisms such as emulation do not equate to cumulative culture (Marshall-Pescini and Whiten, 2008; Wilkins, 2019). While a number of studies on chimpanzee knowledge acquisition both in the wild and in captivity argued for the potential importance of social learning, only a small subset of these studies argued for social learning reminiscent of cumulative culture and high-fidelity transmission contexts (Biro et al., 2003; Horner and Whiten, 2005; Marshall-Pescini and Whiten, 2008; Whiten et al., 2009a). Since the error bars on the ages for the Koobi Fora sites are large, it is appropriate to state that the independent reinvention versus knowledge transmission debate is still difficult to assess with currently available data.

The first way to address the possible presence of social learning in the early Acheulean would be to develop predictions as to whether the technologies needed to be learnt. In other words if early Acheulean technologies entailed too many hierarchically nested manufacturing steps (Stout, 2011; Muller et al., 2017) for individual hominins to learn in the course of a single lifetime, these steps would have needed to have been learned for these technologies to persist.

Secondly, comparisons between the early Acheulean in Koobi Fora and other early Acheulean sites are needed. The nearest early Acheulean sites to Koobi Fora are in West Turkana, Kenya and at Konso Gardula in Ethiopia (Beyene et al., 2013, Lepre et al., 2011). West Turkana is a fascinating prospect as it has a bio-geographical barrier with Koobi Fora in the form of the lake itself and the massive Omo river. The Konso Gardula region has a number of archaeological sites, such as KGA7-A1, A2, A3 that correspond to the age of the Koobi Fora localities (Beyene et al., 2013). If two geographically separated hominin groups in the regions of Konso Gardula and Koobi Fora produced the same technologies, yet these technologies had very few hierarchically nested steps (Stout, 2011), then it seems more plausible that such technologies may have been independently developed by these groups in these different regions.

3.3. Perspectives on the spatial organization of Acheulean technology

The processes of LCT production adopted by hominin toolmakers were results of their physiological, cultural, economic, and environmental domains, as well as the nuanced interactions between these domains (Nelson, 1991). Chapter 3.2. outlined an LCT production method that was documented across all four early Acheulean assemblages from Koobi Fora. However, the production system itself provides only a small window onto the system of hominin behaviour. A broader window appears when this LCT production system is viewed in its interaction with landscape and hominin mobility patterns (Binford, 1979; Kelly, 1988). Hominins were not only practising a specific method to make LCTs, they were also adapting this method to variability in the resource framework – the opportunities to make and use tools – across the landscape. To understand this interaction we need to analyse assemblages holistically (Carr and Bradbury, 2011a).

Different proxies including raw material transport and discard patterns indicate that, in addition to evidence for the production of LCTs, the earlier Acheulean also documents substantial shifts in the way the landscape was used by hominins (Hay, 1976). 'Site fragmentation', which refers to spatially structured artefact discard patterns, appears archaeologically as if artefact manufacture cycles at different sites have been interrupted (Hallos, 2005). In other words, fragmented assemblages represent windows onto a continuous but spatially differentiated artefact manufacture system. This phenomenon has implications for hominin mobility, site functional variation and occupation intensity (Hallos, 2005; Goren-Inbar and Sharon, 2006; de la Torre et al., 2014). Degrees of site fragmentation are also linked with planning depth, which have implications for hominin cognition and working memory (Atance and O'Neill, 2001; Hallos, 2005). In this thesis the concept of site fragmentation provides a lens through which to examine hominin technological organization from a landscape perspective.

In contrast to Oldowan sites that frequently have complete artefact life cycles (Semaw, 2000; Delagnes and Roche, 2005), later Acheulean sites are frequently fragmented. For example, bifacial LCTs from Kilombe and Olorgesailie in Kenya were transported to the sites in fully manufactured form, and were only re-sharpened at these sites (Isaac, 1977; Crompton and Gowlett, 1993). Site fragmentation and spatially structured differential discard is also evident among several contemporaneous late Acheulean sites at Mieso, Ethiopia (de la Torre et al., 2014).

Prior to this study there has been little published on early Acheulean technological organization. Further, whether early Acheulean hominins were planning their technological activities in substantial anticipation of future needs, as is demonstrated for later Acheulean contexts, is also unknown (Hallos, 2005).

3.3.1. LCT production patterns, hominin mobility and site function

The analysis was undertaken to investigate how the trajectory of shape change associated with reduction differed between the four archaeological sites, when the sites are viewed independently. Patterns of LCT shape variation at FxJj63 and FxJj65 looked very similar and represented the full life-history of biface production. Both sites had the combination of (1) marginally reduced LCTs which resembled the original shape of the blanks, (2) elongated specimens with marginal removals along their edges that resemble pick-like LCTs and (3) a lower proportion of discoid-like, intensively reduced LCTs. The LCT forms at FxJj37 and FxJj21, however, represented different fragments of LCT life history as the initial flake blanks as well as the elongated stage of LCT life history were missing from these sites.

There appeared to be a landscape scale compartmentalization of different stages of LCT reduction at Koobi Fora (Hallos, 2005). Unlike FxJj65 and FxJj63 that had the full sequence of LCT production, at the sites of FxJj21 and FxJj37 several stages of LCT manufacture were missing. At the latter sites, LCTs appeared to be far more heavily reduced and there was little evidence of early stage manufacture.

To further understand site function in relation to LCT production, other analyses focusing on large flake blank production patterns and artefact densities were undertaken. At the site of FxJj65 unmodified large flakes were present, but boulder cores were lacking. That suggested that LCT blanks were likely manufactured off-site, but perhaps in close proximity to the FxJj65 locality.

Large flake blanks for LCT manufacture were produced on-site at the locality of FxJj63. There were two boulder cores with multiple removals at FxJj63. One of these cores had a prepared knapping platform and two to three big flake removals. A refit between a large flake blank and this core showed that the Kombewa method was employed.

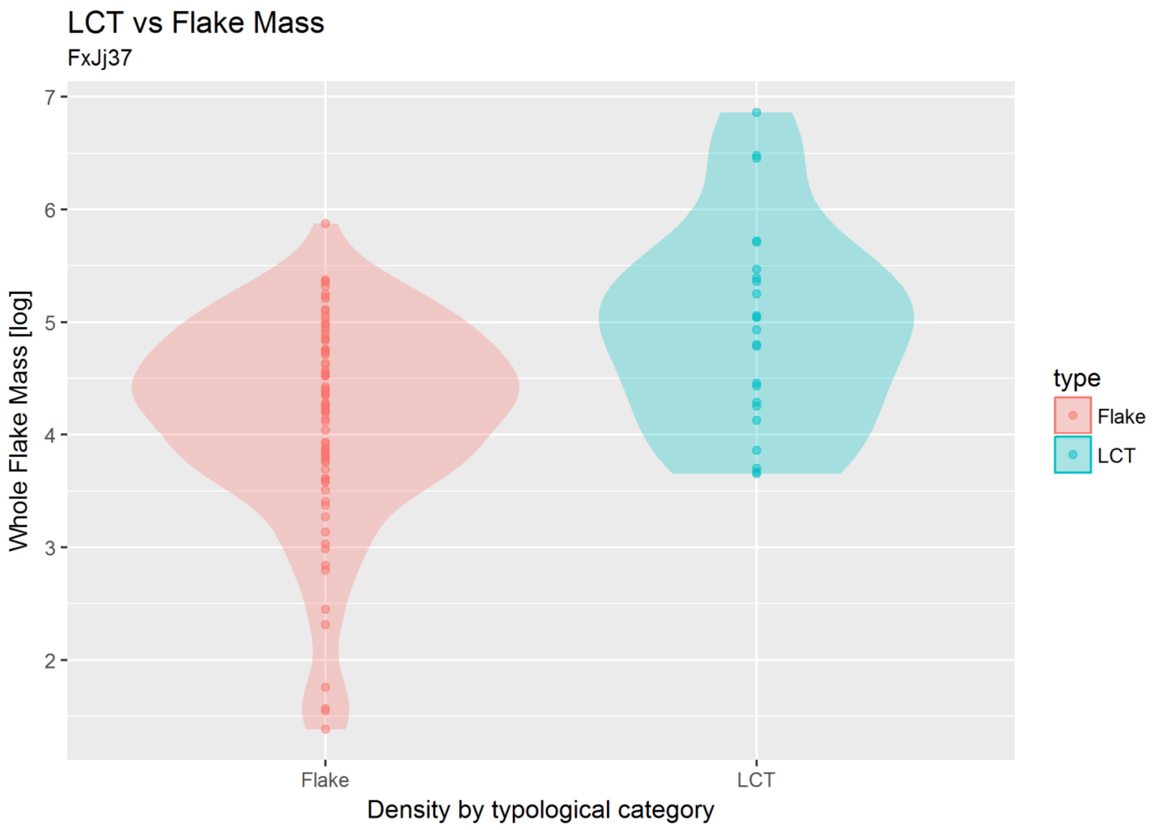

Figure 3.4. Violin plot comparing flake and LCT mass (gr) from FxJj37. Plot made using ggplot2 package in R (Wickham, 2009).

In stark contrast to FxJj63 and FxJj65, there was no evidence for on-site LCT blank production at FxJj37 and FxJj21, and there was an absence of sizable cores. In addition, a significant difference existed in the size of unworked flakes at FxJj37 compared with flakes which had been shaped into LCTs (measured by both mass and volume) (Figure 3.4). This contrast suggested that LCTs were made elsewhere.

FxJj37 and FxJj21 also had relatively low assemblage level cortex coverage, and had lower frequencies and smaller sizes of all lithic artefacts than the other sites. These general characteristics were suggestive of the later stages of tool life history. Further, small numbers of finds and normal distributions of artefact sizes at FxJj37 and FxJj21 contrasted with high numbers of finds and multimodal distributions of artefact sizes at the sites of FxJj65 and FxJj63. One would expect such multi-modal distributions at sites that had flakes as bi-products of different phases of LCT manufacture in addition to larger flakes that formed part of LCT blank production. One would expect this distribution to occur at sites where hominins were making tools or gearing up (Binford, 1979; Bleed, 1986; Bousman, 1993).

Early Acheulean artefacts at Koobi Fora were likely to have been manufactured at specific places on the landscape, such as at the site of FxJj63. Further evidence for the presence of specific manufacturing localities is provided by the refitting of a large LCT blank to the core from which it was struck at FxJj63, in addition to the frequency of LCTs at this same locality which had been abandoned after only a small number of removals. LCTs were then transported by hominins away from these LCT manufacturing localities, and were resharpened and discarded in different places on the landscape, such as at the localities of FxJj37 and FxJj21.

The reconstruction of early Acheulean artefact discard patterns relative to known sources of raw material suggests a disparity in landscape use and mobility patterns between Oldowan and Acheulean tool producing hominins (Hay, 1976). Distance to raw material sources is a variable that may have affected hominin mobility patterns and, contingently, artefact morphological variability and typological compositions, as well as assemblage densities (Féblot-Augustins, 1993; Potts et al., 1999; Blumenschine et al., 2012). Hence, the expectation developed for the early Acheulean at Koobi Fora is that sites closer to the basalt outcrop would have less reduced LCTs than sites further away. However, after analysing minimal distances to raw material outcrops, it turned out that there was no correlation between the distance to raw materials and tool reduction intensity. For instance, the site of FxJj37, which had the most extensively reduced LCTs, was the closest site to the basalt outcrop, and the tool manufacturing sites of FxJj63 and FxJj65 were unexpectedly much further from the basalt outcrop than FxJj37.

The ~ 1.5 Ma Karari Industry of Koobi Fora, which is a local variant of the 'Developed Oldowan' is an important context to compare raw material use and mobility patterns between the Oldowan and the Acheulean (Harris and Isaac, 1976; Braun et al., 2008b). David Braun and colleagues found a correlation between core reduction intensity and proximity to raw material sources, and proposed that in the Karari assemblages hominins adjusted their artefact procurement and discard patterns in response to raw material procurement opportunities (Braun et al., 2008b).

The study presented in my thesis suggests that perhaps as little as ~110 thousand years later than the Karari Industry, early Acheulean hominins at Koobi Fora appear to have produced, resharpened and discarded their tools in response not only to raw material availability but also other environmental variables such as habitat preference and dietary resources (Quinn et al., 2013; Patterson et al., 2017). Further research will require more paleoenvironmental data to test these ecological explanations quantitatively within my early Acheulean dataset.

Here I show that at the earliest stages of the Acheulean hominins were using a highly mobile technological system. Whether this pattern of spatial fragmentation in technological organization was specific to the Koobi Fora sites, or whether similar technological organisation was present at other early Acheulean localities would need to be addressed in future research. However, there is some evidence suggesting that Koobi Fora might not be unique, as off-site large flake production patterns have been described for some other early Acheulean localities such as Peninj and Melka Kunture (de la Torre et al., 2008; Gallotti, 2013), and therefore may be a more common feature of landscape-scale patterns of early Acheulean LCT production.

3.3.2. Site fragmentation and landscape use in the Acheulean

Chapter 3.1.1. described a method for quantitatively distinguishing the products of *débitage* and *façonnage* strategies within Acheulean contexts. The results suggested that the majority of flakes in the assemblage were the products of core and flake like technological strategies, while the LCTs were made elsewhere and transported to the Elandsfontein Cutting 10 locality in their reduced form. These findings are revisited here with the goal of comparing site fragmentation patterns between early Acheulean sites (Koobi Fora) and the late Acheulean (Elandsfontein).

Several researchers previously advanced the idea that LCTs at Elandsfontein Cutting 10 were probably made off site. As such, Singer & Wymer (Singer and Wymer, 1968) proposed that flakes recovered at this locality were unlikely to be related to the production of LCTs as there were so few of them. Archer and Braun's 2010 3DGM study of LCTs from Elandsfontein concluded that most LCTs were in their final reduction stages. By demonstrating that the majority of flakes in the assemblage were the products of Mode 1 like technological strategies, the findings of Presnyakova et al. 2015 confirmed the suggestion that the LCTs were indeed made elsewhere and transported to the Elandsfontein Cutting 10 locality in their reduced form.

Past research and my analysis indicated the presence of two distinct technological strategies practised at the Cutting 10 locality. One strategy entailed the onsite reduction and discard of Mode 1 cores along with their associated *débitage*. LCT forms, transported to the site in a reduced state and then discarded, represented the second strategy. This suggests that hominins at Elandsfontein Cutting 10 varied decisions regarding the discard and maintenance of the products of different technological systems based on different contextual factors. Exactly what were these contextual factors and how they played a role remains thus far unclear. At present it is possible to speculate that a heterogeneous landscape at Elandsfontein with the localized landscape features in the form of springs and vegetated areas could have been at least one of these contextual factors (Patterson et al., 2015), another factor could have been the distribution of secondary raw material sources on the landscape (Braun et al., 2008a).

My analyses of the early Acheulean sites in Koobi Fora demonstrated spatially structured artefact discard patterns. I interpreted this fragmentation as the consequence of site functional variability and differential landscape use by hominins, which may be reflective of unexpectedly in-depth planning abilities (Hallos, 2005).

The Elandsfontein data also revealed a fragmented pattern in LCT production, and indicated the importance of Mode 1 *débitage* production even in assemblages where the counts of LCTs and cores suggest that LCT production was the major technological strategy. The data from both regions make it appear that technological organization between the early and the late Acheulean shared similarities such as reduction sequence fragmentation across the landscape, which is not observed in any Oldowan sites.

At Elandsfontein Cutting 10, several production stages were missing and LCTs entered the record in a ready to use form. It is still not clear, however, what LCTs were used for (see Chapter 1.3.), so this phrase that something was ‘in a ready to use form’ has a rather abstract meaning. Nevertheless, data from Elandsfontein allows one to infer that LCT edge maintenance took place at the site, without extensive roughing out or shaping.

The fragmentation pattern at Koobi Fora was different. FxJj37 and FxJj21 sites had only very early and very late stages of manufacture. Therefore, Elandsfontein, FxJj21 and FxJj37, had fragmented sequences, but the nature of this fragmentation was very different. Substantial LCT variation was present at all three localities, Elandsfontein LCTs appeared far more standardized than FxJj37 and FxJj21.

One site that does appear to have a similar organization to Elandsfontein is Mieso 7 in Ethiopia. This locality is interesting as, unlike the many other later sites with debatable site formation such as Kalambo Falls or some of Olorgesailie sites, there is a minimal indication of non-hominin agents influencing artefact concentrations at Mieso (de la Torre et al., 2014). Mieso 7, had patterns of fragmentation similar to Elandsfontein where shaping occurred prior to the appearance of LCTs at the site. LCTs appeared in very late stages of reduction, and only a few flakes related to *débitage* were found (de la Torre et al., 2014).

At the other site, Mieso 31, about 3 km away from Mieso 7, LCTs were produced at the site and subsequently were taken away (de la Torre et al., 2014). This pattern of fragmentation is similar to the Boxgrove site GTP17-Unit 4b in the UK, that had most elements of bifacial reduction but was missing LCTs from the intermediate stage. The complete or nearly complete production sequences at FxJj65 and FxJj63 are very unlike Mieso 31 or Boxgrove, as the former localities only retain the initial phases of production.

The differences in technological organization between the early and the late Acheulean warrants further research. For instance, late Acheulean sites such as Montagu Cave has non-fragmented production sequences may provide a good comparative point with which to contrast early Acheulean sites that have fragmented patterns (Keller, 1973). This kind of comparison may shed light on whether the difference in fragmentation patterns between the early and the late Acheulean is underpinned by shifts in hominin behaviours.

Philip Carr and Andrew Bradburry (2011), as well as other researchers who extensively investigate technological organization, argue for the importance of studying all elements of any assemblage. In this vein, I will now discuss non-LCT Acheulean lithics. Reviews of the time period when the Acheulean first appeared often suggest that this technology rapidly replaced Oldowan core and flake technology (Foley and Lahr, 1997, 2003; de la Torre and Mora, 2013). However, both the Koobi Fora early Acheulean sites and Elandsfontein Cutting 10 indicate the importance of Oldowan like flake production, even in assemblages where the counts of LCTs and cores suggest that LCT production was the major technological strategy.

The presence of Oldowan like cores within different temporal contexts is possibly suggestive of a general diversity within the Acheulean toolkit (de la Torre et al., 2008; de la Torre, 2011; de la Torre and Mora, 2018). Cleavers are flake based tools that are technologically different from handaxes and have been described mostly within later Acheulean localities (Inizan et al., 1999; Gallotti et al., 2010). Simple Oldowan like cores, cleavers, and flake production may reflect different components of a technological system relative to LCTs, and perhaps underpin different aspects of hominin technological strategies (Carr and Bradbury, 2011a; Kuhn, 2012).

While Oldowan like cores LCTs and cleavers co-occurred at many sites, the hindrance to analysing these aggregates as hominin ‘toolkits’ might be a time averaging issue. In time-averaged contexts, the co-occurrence of different artefact types may, potentially, be suggestive of complex site formation processes and diverse behavioural explanations rather than versatile toolkits.

Nicola Stern (Stern, 1994) argued that all Pleistocene archaeological sites consisted of palimpsests of artefacts that could have accumulated in periods ranging from thousands, to hundreds of thousands of years. Because of time averaging, Stern suggested that searching for contemporaneous sites was unproductive, and criticized former attempts to recreate landscape scale behaviours in the Stone Age. In this vein, my study did not aim to recreate activities that have simultaneously taken place on past landscapes at Koobi Fora or Elandsfontein. The logic behind referring to the Koobi Fora sites as quasi-contemporaneous implied little time differences in an evolutionary sense of scale, i.e. the time significant in major physiological, behavioural, and climatic changes occurring. The study at Koobi Fora focused on geographic patterns of hominin landscape use that did not necessarily occur at once, but likely occurred within the same landscape scale of resources. The sites discussed here likely represent instances of rapid sediment accumulation. All four sites from Koobi Fora were in close proximity to active channels/rivers. Fluvial activities, while not in the floodplain stage, tend to have high sediment accumulation rates (Feibel et al., 2009). Singer and Wymer and later Richard Klein described faunal remains from Elandsfontein Cutting 10 site as mostly disarticulated but certainly with some articulated specimens, and all are well preserved (Singer and Wymer, 1968; Klein, 1978). The bone preservation and semi-articulated state of certain specimens (Braun et al., 2013) suggest that the site was likely submerged under aeolian sand relatively quickly.

Does rapid sedimentation result in sites that are not time averaged? Harold Dibble and colleagues wrote a paper about common fallacies in archaeology. One of these common fallacies was the idea that contemporaneous assemblages exist at all (Dibble et al., 2017). The authors suggested that a single geological unit was not equivalent to a single archaeological assemblage. The issue with any locality in the Pleistocene is that even if we show that sediments have been rapidly accumulating, it does not mean that artefacts belong to a single episode of occupation, or that there is a way to decipher several occupations (Dibble et al., 2017). If Elandsfontein Cutting 10 and Koobi Fora could have been rapidly buried sites, which according to Dibble does not eliminate time-averaging, these localities still should be viewed as palimpsests.

Nicola Stern, however, urged not to view time-averaging as an impediment to hominin behaviour, as even time-averaged assemblages produce behavioural signals (Stern et al., 1993). Even if Elandsfontein Cutting 10 aggregates of artefacts were the results of a thousand-year accumulation, this would suggest many generations of hominins probably conducted butchering activities at the same locality, but never manufactured their LCTs at this locality.

Then at FxJj37, although hominins potentially manufactured and discarded artefacts thousands of years apart, LCTs in the initial reduction stages were still missing. In time-averaged contexts, the co-occurrence of Oldowan like cores and LCTs may suggest that several groups at different times with different technologies used the same locality in the very same way. Alternatively that hominin land-use patterns were changing with time, possibly as a response to environmental shifts that triggered the shifts between Oldowan and Acheulean strategies.

Earlier in this section I mentioned Margaret Nelson (1991), who created a hierarchical framework for understanding technological organization. Philip Carr and Andrew Bradbury (2011) later added multiple interactions between the elements of a technological framework. From this framework it appears that environmental conditions provide a causative terrain for hominin behavioural responses. Environment influences socio-economic strategies, while both environment and socio-economics affect the technological strategies adopted by hominins. Artefact design and form variability emerge from the different technological strategies applied by hominins, as well as the distribution of activities on a landscape, and the artefact distribution within a site.

It appears that at least for the ESA, this entire interpretive framework is influenced by random effects. By random effects I mean any factors or covariates for which the effects are difficult to predict, or to formulate hypotheses about their influence. Yet random effects certainly may influence the accuracy of behavioural explanations drawn from archaeological patterns. These random effects could include hominin physiology and fine-motor control, and demography that changed through time and across space in the past, in addition to potential taphonomic effects such as time-averaging.

In Chapter 1.2.3. I discussed the Panda 100 site in the Taï Forest, Cote d'Ivoire, which provided a description of chimpanzees habitually transporting hammerstones away from nut-cracking sites, hence creating fragmented assemblages (Proffitt et al., 2018). Prior to the study of Proffitt and colleagues, similar observations of chimpanzee transport behaviours were reported by Christophe Boesch (Boesch and Boesch, 1990; Boesch et al., 2017) and Susana Carvalho (Carvalho et al., 2008).

Low numbers of artefacts in the chimpanzee nut-cracking kit in addition to short distances of transport characterize the one extreme of the spectrum one could expect of the hominin record. The other extreme of the spectrum is characterized by complex ethnographic patterns and predictions for highly mobile multi-component tool-kits that may vary over geographic scales of many hundreds of kilometres (Yellen and Harpending, 1972; Yellen, 1977; Binford, 1979, 1980). These ethnographies describe behavioural phenomena driven by environmental, demographic and socio-economic contexts wherein responsive technological strategies emerged (Carr and Bradbury, 2011a). Clearly the plethora of modern human technological responses and of the diversity possible interactions with different environments are far more complex than chimpanzee artefact transport. I ought to mention here that this comparison is not a comparison of cognitive capacity, this is a comparison of the complexity of technological organization. The complexity of Neanderthal technological organization in comparison to modern humans is a debatable topic as some see the Neanderthal organization as paralleling (Conard and Adler, 1997; Turq et al., 2013), while others disagree (Binford, 1985).

For earlier technological systems like the Acheulean, where no reliable modern analogies exist, it is difficult to determine an appropriate place on this trans-hominoid spectrum of technological organization. The limited data that are available indicate that certain aspects of modern technological organization may be present in the Acheulean, such as in depth levels of planning in the manufacture of artefacts that are intended for future use resulting in sequence fragmentations. This thesis in particular focused on synchronic and diachronic patterns of site fragmentation. The archaeological evidence gathered here suggests that both early and late Acheulean hominins made artefacts in substantial anticipation of future use. The data are not resolved enough to assess whether this planning extended beyond daily activities. From the perspective of Koobi Fora and Elandsfontein, planning patterns, or mechanisms underpinning fragmented production, might have changed from the early to the later Acheulean. Importantly, whether and to what degree Acheulean hominins planned their activities in advance of future work remains an open topic that will benefit from future research.

CHAPTER 4. CONCLUSION

This thesis proposed several new avenues in the investigation of the role of Acheulean technologies in the evolution of hominin behaviour. The two main methodological objectives of this study were (1) to develop a model to quantitatively discriminate shaping (*façonnage*) from non-shaping (*débitage*) Early Stone Age products and (2) to characterize and quantify the shapes of early Acheulean LCTs using an appropriate 3DGM approach.

These new methods were then applied to the archaeological record, and the generated data were integrated with other qualitative and quantitative data sources including the findings of *chaîne opératoire* and attribute analyses. The purposes of this archaeological application were to (i) study broader geographic patterns of landscape usage among early Acheulean sites, and to (ii) compare and contrast patterns of technological organization between the early and later Acheulean. The contribution of this study is therefore two-fold, in (a) developing two new methodological models for investigating Acheulean technology and in (b) using the results from the application of these models to build hypotheses about the role of the Acheulean in the evolution of hominin behaviour in Africa. I lay out below some suggestions for future studies that may build on findings presented in this thesis.

To summarise, Presnyakova et al. 2015 (Appendix 1) examined morphological variation among flakes produced with Early Stone Age “core and flake” technologies and flakes resulting from bifacial shaping. A combination of Discriminant Function Analysis and the Generalized Linear Model were used to investigate systematic variation between the flakes of interest. First, an experimentally produced assemblage was used to build the models. Then the models were applied to the archaeological collection from Elandsfontein Cutting 10, in South Africa.

The flake shape model enabled the classification of Cutting 10 archaeological flakes in terms of their probability of association, within either shaping or *débitage* technological groups. Such automated classifications of archaeological materials could, in my opinion, be fruitfully applied to other contexts and a future objective is to apply this model to earlier Acheulean contexts. Throughout this thesis I highlighted the potential importance of focusing on the previously understudied Acheulean flake production record, to address questions about site function, landscape use and technological organization. I feel that the application of my predictive model to other earlier Acheulean contexts could make a valid contribution to these three respects.

The so-called ‘bifacial shaping technique’ is widely assumed to represent the hallmark of the Acheulean (Inizan et al., 1999), which has even lead some researchers like Lepre and colleagues (2011) to contend that (a) the earliest Acheulean and (b) the onset of bifacial shaping are synonymous with one another. Other scientists express far more caution in concluding that crude early Acheulean LCTs have been shaped intentionally in a comparable way to later Acheulean LCTs (Beyne et al., 2013, Torre and Mora 2005, Ludwig and Harris 1999, Roche et al. 2003, Gallotti 2013, Stout 2011).

My position is that this question needs to be quantitatively investigated. My predictive model of deciphering flake types may be useful in resolving the question of (1) which flakes in the early Acheulean record related to shaping, and (2) when we first see these, difficult to recognize, shaping flakes in the African archaeological record. Placing early Acheulean flakes on a morphological continuum from ‘typically’ shaping to ‘typically’ *débitage* would likely provide some insight on this issue, and on the timing of the emergence of the shaping technique in the African record.

Presnyakova et al. 2018 took a broad landscape-scale approach to analysing LCT variability among four semi-contemporaneous early Acheulean sites using 3DGM. The 3DGM results were then contextualized against other indicators of hominin landscape use to draw inferences about foraging ranges, mobility and tool transport distances, strategies of stone raw material procurement and use and spatial depths of planning in the organization of stone tool production in the early Acheulean. This study demonstrated that a variable range of LCT forms across the landscape fell on a single early Acheulean reduction trajectory for the four sites analysed. I was then able to compare and contrast manufacturing and maintenance trajectories between early Acheulean localities, and assess how different localities related to one another within a single framework of hominin landscape use.

The question of how Acheulean technologies were organized has received considerable attention in this thesis and, in my opinion, is a topic that would benefit from much more future research. For instance, typically Oldowan core and flake technologies that co-occur with Acheulean bifaces in the same assemblages raise several questions. The most important question being: does the co-occurrence of these technologies reflect attributes of hominin technological organization? Considering the potential time-averaging issues that were discussed previously (see Chapter 3.3.), studying broader temporal patterns of Mode 1 and Mode 2 co-occurrences may enable the detection of 'averaged' behavioural signals that would inform about the organization of technology evolves through the later Oldowan and early Acheulean.

If we compare several Acheulean localities that have both Acheulean LCTs and Mode 1 like cores, would we find a predictable pattern in the ways Mode 1 and Mode 2 products occur together? Such a pattern could be explored with measures such as proportions of cores to LCTs, represented reduction stages of both technologies at different localities, raw material types and raw material sources represented.

Another potentially fruitful avenue would be to study variability in *débitage* strategies at early Acheulean localities. For example, in early Acheulean flake production systems, some archaeologists have documented a departure from the classical Oldowan core reduction scheme, and a shift towards the hierarchical organization of surfaces (de la Torre and Mora 2005; Leader et al. 2016). The question then arises, do Oldowan like-Mode 1 cores increase in complexity through the Acheulean?

We live in analytically exciting times, with rapidly evolving and increased accessibility of novel approaches such as machine learning and artificial intelligence ('AI'), Generalized Linear Mixed Models and simulations. We ought to make use of such analytical tools in Early Stone Age research, in studies of hominin behavioural variability and behavioural evolution. Free platforms such as R or Python, and extensive online support are available to us in our further investigations of the Acheulean, for instance, to study technological organization and site functions from new perspectives. To interpret archaeological assemblages that are the products of a diverse and multivariate network of variables including complex hominin lifeways, as well as taphonomic processes - a scenario that gets only more complicated in deeper swathes of time - we need to develop new methodologies.

The expansion of hominin foraging ranges involving increased mobility and tool transport distances, variability in strategies of stone raw material procurement and use, increased spatial and temporal depths of planning in the organization of stone tool production, are all features that, in the literature, are nearly synonymous with the onset of the Acheulean. But does this technology mark a key adaptive leap in hominin behavioural evolution? This thesis makes a number of arguments about how shifts in hominin behaviour and cognition are manifested archaeologically in the early Acheulean record, but much more work is needed. My hope is that some of the potential studies I outlined above will provide future insights into the role of the Acheulean in human evolutionary history, and in particular, whether some features traditionally viewed as occurring exclusively within the uniquely modern human condition, may actually be rooted in much deeper time.

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Appendix I.

RESEARCH ARTICLE

Documenting Differences between Early Stone Age Flake Production Systems: An Experimental Model and Archaeological Verification

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Abstract

This study investigates morphological differences between flakes produced via "core and flake" technologies and those resulting from bifacial shaping strategies. We investigate systematic variation between two technological groups of flakes using experimentally produced assemblages, and then apply the experimental model to the Cutting 10 Mid -Pleistocene archaeological collection from Elandsfontein, South Africa. We argue that a specific set of independent variables—and their interactions—including external platform angle, platform depth, measures of thickness variance and flake curvature should distinguish between these two technological groups. The role of these variables in technological group separation was further investigated using the Generalized Linear Model as well as Linear Discriminant Analysis. The Discriminant model was used to classify archaeological flakes from the Cutting 10 locality in terms of their probability of association, within either experimentally developed technological group. The results indicate that the selected independent variables play a central role in separating core and flake from bifacial technologies. Thickness evenness and curvature had the greatest effect sizes in both the Generalized Linear and Discriminant models. Interestingly the interaction between thickness evenness and platform depth was significant and played an important role in influencing technological group membership. The identified interaction emphasizes the complexity in attempting to distinguish flake production strategies based on flake morphological attributes. The results of the discriminant function analysis demonstrate that the majority of flakes at the Cutting 10 locality were not associated with the production of the numerous Large Cutting Tools found at the site, which corresponds with previous suggestions regarding technological behaviors reflected in this assemblage.

Introduction

Acheulean lithic technologies are first recognizable in East Africa by approximately 1.7 Ma at the sites of Kokiselei 4, West Turkana, Kenya [1] and Konso Gardula in Ethiopia [2]. The Acheulean persisted for more than a million years as evidenced by east African later Acheulean sites between 500–200 ka such as Olorgesailie Member 14 [3], Isimila [4], sites LH and FS in the Kapthurin formation [5] as well as Wonderwerk Cave [6] in South Africa and 8-B-11 in Sudan [7].

The production of Acheulean bifacial Large Cutting Tools [8] (hereafter "LCTs") remains the most characteristic and recognizable technology by which Acheulean industries are traditionally identified [9]. However, innovations associated with the appearance of the Acheulean are manifested within a broader technological system than production of the bifacial forms themselves [10–12].

Relative to chronologically preceding industries, Acheulean technologies are argued to represent increased complexity in (1) raw material procurement and selection patterns [13–18], (2) provisioning systems and mobility [19,20] as well as (3) tentatively, a possible increase in levels of socially mediated information transfer within and between artifact producing groups [21–23].

The Acheulean is also associated with the emergence of broadly systematic bifacial shaping. In the context of handaxe production this shaping initiates through the roughing out of selected blanks, and is followed by a sequence of finishing stages aimed at thinning, as well as refining bilateral and bifacial symmetry [24]. It has been suggested that *debitage* is the intentional fracturing of a volume of raw material to produce flakes, whereas *shaping* is applied to reduce a volume of raw material with a template or notion of preconceived bifacial form [24].

Cores, viewed independently, are capable of revealing information about morphology associated with reduction strategy, intensity and perhaps even function in the context of certain core tools [25–28]. However, a broader understanding of Middle Pleistocene technological organization is attainable only by studying all parts of the technological system[29].

In this vein the byproducts of bifacial shaping that are unequivocally associated with LCT production x and their distribution on the landscape—are as important proxies for Acheulean technological behavior as the shaped LCTs themselves [30,31]. Conversely, detached pieces within Acheulean assemblages that are not byproducts of LCT production contain valuable information about variability in Acheulean technological behaviors [13,32].

Here we develop an experimental framework using morphometric data and multivariate statistics to quantify variation in flakes produced (1) within the application of roughing out and bifacial shaping strategies as well as (2) via a discrete set of flake production strategies identified within Oldowan industries. To test the validity of our methodological framework as well as its suitability to archaeological materials, we analyze the archaeological collection of whole flakes from the well-studied Mid-Pleistocene site of Cutting 10 from Elandsfontein [18,33].

Previous descriptive and typological analyses of the materials from Cutting 10 suggested that the numerous bifacial tools recovered at this locality were not produced there [33]. The Elandsfontein locality is a well-studied collection of Mid-Pleistocene tools that have been recovered in association with an extensive fossil assemblage [34,35]. Our analysis supports previous assertions that LCT production occurred elsewhere on the landscape, and that LCTs were transported to the Cutting 10 locality in finished form prior to discard [33]. Additionally, flake products were produced on site that had no technological association with the LCT component of the Cutting 10 assemblage. We describe the application of our methodology to the Cutting 10 collection to demonstrate its utility to documenting landscape scale variation in patterns of Middle-Pleistocene tool manufacture, maintenance and discard in ways that are quantitatively replicable and comparable.

Importantly, in this paper the 'Modes' terminology will be used as a reference to technological forms. Graham Clark defined Oldowan or "core and flake" technology as Mode 1, and bifacial industries as Mode 2 [36,37]. Importantly, the "Mode" terminology used in this paper is not applied in the sense of a evolutionary trajectory [38], or to associate industries with distinct hominin groups [39]. Here we use the terms Mode 1 and Mode 2 for heuristic purposes only as baseline descriptive concepts [40]. Further, instead of referring to bifaces we will use the term "LCT" [10].

Background

In the 1950s-1970s Acheulean sites were traditionally and widely identified by the presence/absence of characteristic bifacial forms [41].Characteristic LCTs were subsequently divided into categories ranging from primitive to more advanced [42,43]. For example Kleindienst used LCT percentages to classify sites at Olduvai Gorge as either Acheulean or Oldowan [44]. Mary Leakey used the presence/absence criteria in association with LCT frequencies to define the term Developed Oldowan [43]. According to Leakey "Developed Oldowan A" was an Oldowan toolkit that also had proto-bifacial elements present. "Developed Oldowan B" necessarily had to have a certain percentage of bifacial pieces within the toolkit More recently researchers have suggested that "Developed Oldowan" in general should rather be referred to as Acheulean [45].

The technological approach that flourished during the 1980–90s focused on LCT variability purportedly associated with differences in tool function [46–50], factors driving morphological variability [14,15,51–57] and patterns of reduction [11,12,45,58–61]. However, we outline two scenarios below that potentially warrant formulation of a different approach to investigating Acheulean technological behavior.

A. Acheulean sites where diagnostic LCTs are absent

Numerous sites have been classified as Acheulean, but their attributions remain contentious due to lack of traditional characteristics, namely, absence of classical LCTs. For example, as LCTs are often made on flake blanks it was suggested that the presence of systematic large flake production may be a diagnostic criteria of the Acheulean technocomplex in contexts where the LCTs themselves were not present [62,63]. A number of Pleistocene sites have consequently been identified as being representative of the Acheulean solely on evidence for large flake production. Some examples include FC West, Olduvai Gorge [45], Kokiselei 4, West Turkana [64], and FxJj 63 in Koobi Fora [62].

Examples of Acheulean sites with no LCTs are also known from much younger Middle Pleistocene contexts. For instance, The Nadung'a 4 locality in West Turkana is a Middle Pleistocene site dated to around 700 ka. Artifact assemblages at Nadung'a 4 contain denticulates and notches, but no LCTs have been identified [65]. Likewise, layers V-5 and V-6 at Gesher Benot Ya'aqov, Israel contain no LCTs but were assigned to the Acheulean through characterization of technological aspects of flake collections [63]. The purported absence of LCTs at many Middle Pleistocene sites in eastern Asia is significant [66], as well as the presence of relatively crudely shaped LCTs at some of the Korean sites, such as Imjin/Hantan River Basin [67].

A plausible explanation for the lack of characteristic LCTs within the assemblages from these localities is that only the early stages within the LCT *chaîne opératoire* are present there. These assemblages may represent windows on the LCT production sequence where blanks or preforms had not yet taken on recognizable bifacial characteristics. By 'blanks' here we mean large flakes or split cobbles, and by 'preforms' we refer to pieces that have been coarsely shaped or 'roughed out' [24].

It has also been suggested that the onset of LCT production represents a shift in hominin raw-material transport decisions [16,17]. It is therefore both plausible and probable that sites exist where both LCTs and/or the blanks intended for LCT manufacture had been transported away from a locality where bifacial strategies were nevertheless practiced [63]. In these contexts, the residual elements of LCT *chaîne opératoire* would be the detached pieces associated with the shaping of LCTs [31,32]. The relationships between flake characteristics and specific reduction processes have been investigated by several authors in the study of more recent bifacial assemblages [68–70]. Therefore, we extend these inferential links here by widening the spectrum of assemblage characteristics through which *shaping* can accurately be identified in an Acheulean context.

B. Acheulean sites where bifacial shaping products co-occur with core and flake technologies

Distinguishing the relative proportions of flakes associated broadly with bifacial shaping from those associated with 'core and flake' debitage strategies may seem qualitatively trivial [71,72]. However, no quantitative method currently exists to quantify these distinctions.

It has been proposed that the emergence of bifacial technology coincided with the demise of core and flake technology [38,73]. This proposed linear trajectory of technological evolution is challenged by Pleistocene sites where simple core and flake products are present in association with LCT manufacture. Examples include Olorgesailie, Kenya [20], Peninj, Tanzania [58], Koobi Fora, Kenya [74] and Gadeb, Ethiopia [59]. In the Middle Awash, there are also Early and Middle Pleistocene sites where Oldowan core and flake technologies overlap chronologically with bifacial technologies [75]. For instance the site of Bodo (> 600k) exhibits only simple core and flake technologies [76]. An important characteristic these examples share is that multiple technological strategies were practiced at the same site. The co-occurrence of several technologies at certain Middle-Pleistocene sites may have been related to the co-existence of multiple hominin lineages [77], the influence of variable environmental settings [78–80] or some other uninvestigated phenomenon.

Materials

Experimental assemblage

We used an experimental assemblage of Mode 1 and 2 flakes to model the effects of sets of independent measures of flake shape on technological group separation. Importantly, within the experimental assemblage the technological group affiliation of each individual flake is known.

The experimental assemblage of Mode 1 and Mode 2 flakes was produced by two experienced knappers (both with more than 10 years of knapping experience). While knapping, the two knappers had no knowledge of the intended usage, and specific archaeological application of the experimental assemblages they were generating. They therefore did not produce flakes in accordance with a specific morphological template. To make the experimental flakes, we used quartzite and silcrete, two of the raw materials exploited at Elandsfontein Cutting 10. In producing the Mode 2 experimental assemblage, the knappers followed the LCT production sequence previously documented for Elandsfontein Cutting 10 by Archer and Braun [18]. The Mode 2 assemblage included 98 flakes generated within the production of 28 LCTs. LCTs were produced by first using a hard hammer and then switching to soft hammer on large (>10cm)

Table 1. Descriptive parameters of the experimental assemblage.

Experimental flakes:	silcrete(n = 77)		quartzite (n = 72)	
Mode 1 (n = 149)	Mean	Sd	Mean	Sd
Length*	57.38	21.74	62.01	19.92
Width	48.95	21.39	59.85	23.45
Thickness	13.98	6.17	16.5	6.43
Mass	66.15	78.91	97.69	88.07
Experimental flakes:	silcrete(n = 93)		quartzite (n = 5)	
Mode 2 (n = 98)	Mean	Sd	Mean	Sd
Length*	36.24	15.08	44.11	13.58
Width	26.77	10.04	32.55	6.42
Thickness	5.38	2.78	7.7	2.98
Mass	8.78	9.35	8.3	4.49

*Technological length, not maximum length.

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side-struck flakes (flakes where the technological length is perpendicular or close to being perpendicular to the maximum length). Side-struck flakes are the dominant blank-form used within the Elandsfontein Cutting 10 LCT collection [18]. Importantly, Mode 2 flakes resulting from roughing out (also referred to as *ébauche)* and thinning (also referred to as *façonnage*) [81] were combined for analytical purposes. Thus, morphological variability within the Mode 2 sample was maximized, to incorporate the maximum potential overlap with Mode 1 flakes in the discrimnant model. In this way shape variation in Mode 2 flakes related to the activities of roughing out and subsequent shaping were both included.

Mode 1 flakes (n = 149) were produced from the reduction of 12 (< 8cm) riverine cobbles. Rounded cortex on many of the cores and flakes from the Cutting 10 assemblage indicate that riverine cobbles were the initial form of many of the cores. To account for some of the documented variation in Mode 1 core reduction strategies [45,82–84] several techniques were utilized including unifacial unidirectional, multidirectional and centripetal (discoidal) [45]. Some of these reduction strategies such as discoidal and multidirectional variants have been identified within the Elandsfontein Cutting 10 collection.

The experimental assemblage consisted of whole flakes. Flakes were considered 'whole' if all of the relevant variables could be measured. The whole flakes were measured using a variety of caliper and digital imaging techniques (i.e. measurements that were made using the photos of flakes). In addition, whole flakes smaller than 2 cm were excluded as it has been suggested that caliper measurements are less reliable and more subjectively variable on flakes smaller than 2 cm [85]. In addition, the digital measurements of curvature used in this study were substantially less precise on small flakes (Table 1).

Archaeological collection

Elandsfontein is a Mid-Pleistocene dunefield on the West Coast of South Africa that has a biostratigraphic age determination between 600kya and 1mya [35]. There is a variety of raw materials represented in the stone tool assemblage. At Elandsfontein Cutting 10 the most frequently used materials were a sub-volcanic rock referred to as quartz porphyry, silcrete, quartzite, quartz and substantially smaller amounts of hornfels (S1 Table). The Elandsfontein Cutting 10 lithic assemblage is from an excavation of *in situ* deposits in the south-east portion of the dune field [34]. The archaeological assemblage from Cutting 10 (Fig 1) consists of 208 artifacts, 66 of

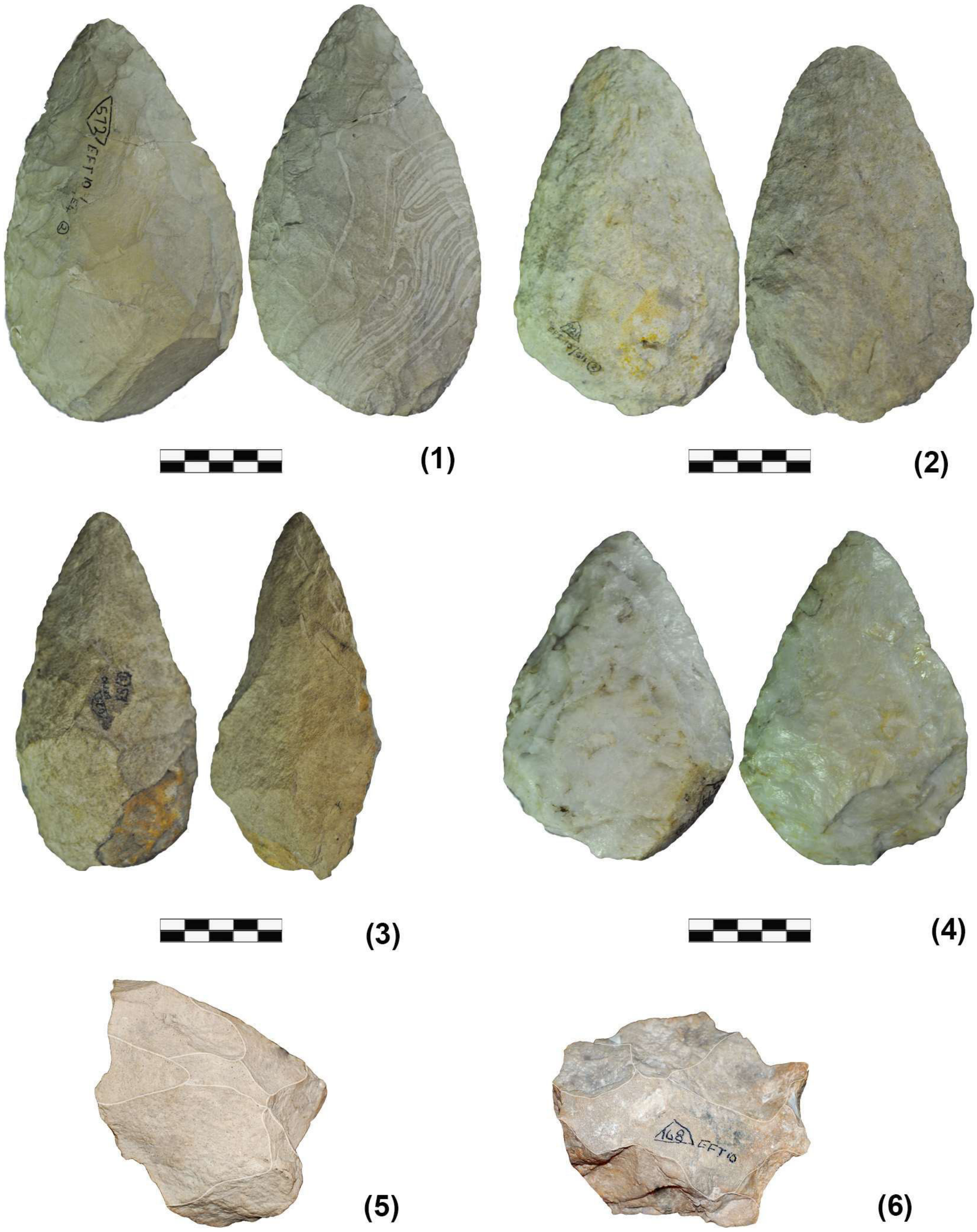

Fig 1. Archaeological specimens. The figure displays Mode 1 cores and Mode 2 LCTs from Elandsfontein Cutting 10 assemblage: (1) EFT_572 (Mode 2: silcrete), (2) EFT_921 (Mode 2:silcrete), (3) EFT_622 (Mode 2:silcrete), (4) EFT_579 (Mode 2:quartz), (5) EFT_182c (Mode1:siclrete), (6) EFT_168a (Mode 1:silcrete).

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which are LCTs, 29 cores and 129 flakes and flake fragments [18,34]. The cores can be classified broadly as discoidal and multidirectional, with short flaking series that do not exceed 3–5 removals. However, multiple series may appear on a given core. Of the 129 flakes and flake fragments, the majority have either post depositional breakages or fractures that potentially occurred during knapping or some other activity (e.g. *siret* flakes). In order to measure all relevant attributes our analysis included the 34 complete archaeological flakes from the

Table 2. Descriptive parameters of the archaeological assemblage.

Archaeological flakes(n = 34)	All raw mat.		quartzite		silcrete		quartz[1]	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Length*	46	15.62	44.05	20.56	46.3	15.7	38.06	10.83
Width	39.68	10.61	59.73	19.95	38.17	9.19	37.67	3.74
Thickness	13.27	4.89	23.25	5.45	12.6	4.34	10.9	2.81
Mass	34.95	25.25	82.75	64.7	32.48	21.07	23.85	5.59

*Technological length, not maximal length.

[1]Hornfels, quartz porphyry and sandstone were only included into "all raw material" category as sample size representing each of these raw materials equals to 1.

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Elandsfontein Cutting 10 collection (Table 2). All analyzed artifacts are currently stored at the Department of Archaeology, University of Cape Town (Cape Town, South Africa). Access to the materials was gained through an agreement between the authors and the Department of Archaeology, University of Cape Town. Permitting details associated with the 1966 excavation of Ronald Singer and John Wymer, are no longer available at the Iziko Museum, Cape Town.

The Elandsfontein Cutting 10 assemblage is particularly suited to investigations into variation in Mid-Pleistocene core reduction strategies for three principal reasons. (1) The collection is comprised of a variety of raw-materials; (2) Sources of stone suitable for artifact manufacture are unavailable within 10 km of the locality [33,86], and (3) both primary and secondary sources of raw material were exploited resulting in marked variability in the range of blank forms exploited [18].

Methodology

Variable selection

Mode 1 cores in general encompass a large variety of core reduction techniques including unifacial, multidirectional and bifacial partial amongst many other variants [45,82,87–89]. However, since these strategies were not applied to achieve a discrete form [24], there are no established guidelines whereby Mode 1 flakes can be identified through their morphological characteristics alone. In contrast, Mode 2 LCT production is applied to develop bifacial and bilateral symmetry of an LCT, while maintaining surface convexities on the LCT [24]. These dual objectives require removing flakes during LCT production, which are characterized by a modal shape or set of shapes.

In terms of modal shape, Mode 2 whole flakes tend to be long and wide, with a relatively small mass, small platforms, concave profiles and are thin relative to Mode 1 flakes [58,90]. However, it would not be possible to incorporate *all* these variables into multivariate analysis as (a) they are correlated with one another, which would result in collinearity, and (b) variables such as length, width or mass are not reliable predictors of shape in themselves as the aspects of shape that they influence are often correlated with overall flake size (e.g. allometry). As such, we have selected a series of variables that focus specifically on the technologically relevant components of whole flake shape:

1. External platform angle (hereafter "EPA") (Fig 2): EPA is the angle measured between the striking platform surface and dorsal surface of a flake directly behind the point of percussion [91–97]. It is one of the few variables which is directly controlled by the knapper [91].

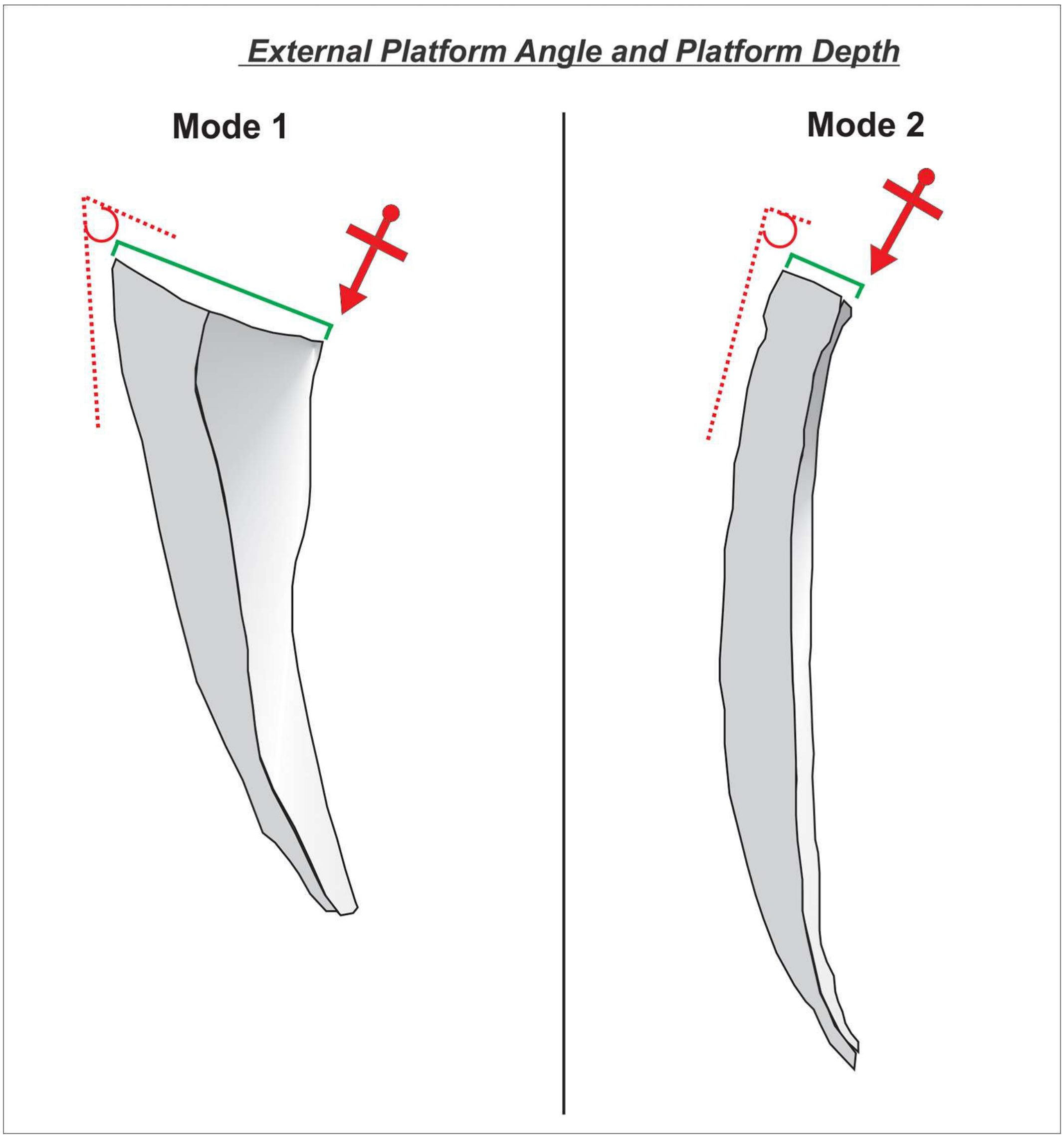

Fig 2. External platform angle and platform depth. Dashed line represents EPA, solid line represents platform depth and arrows are points of percussion.

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Experimental research has demonstrated that EPA influences both flake size and flake morphology [92,93,95].

2. Platform depth (Fig 2): We measured platform depth from the point of percussion to the point of intersection between the platform surface and the dorsal surface of the flake [91]. Experiments have demonstrated that platform depth correlates with overall flake size i.e. an increase in platform depth correlates with an increase in flake mass [91,93]. Prior to the analyses presented here, platform depth was transformed to minimize the effects of allometry (hereafter when we discuss platform depth it is always size adjusted). The variable was standardized by dividing it by the geometric mean of all size related variables such as length, width, thickness and platform width [98]. This size adjustment enables the documentation of shape differences associated with platform variability that are not directly related to size [99].

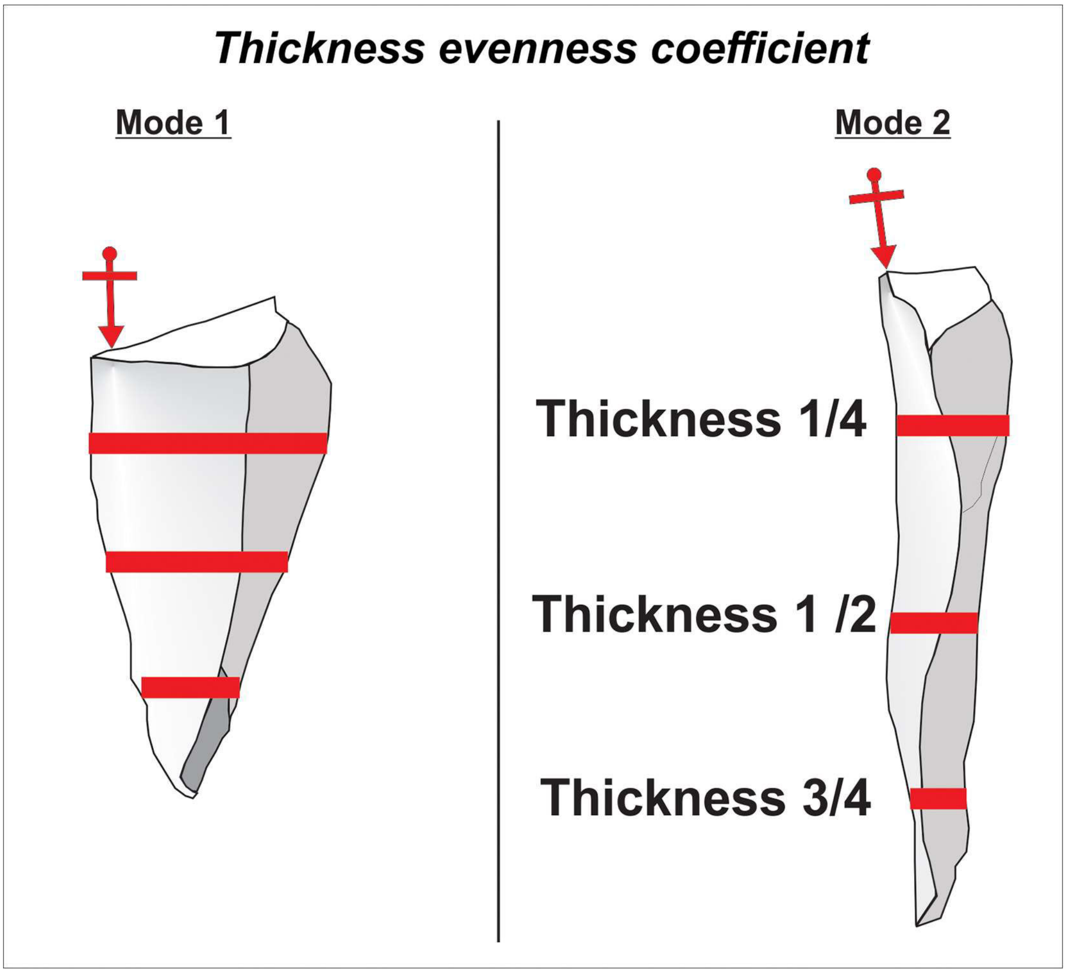

Fig 3. Thickness evenness coefficient. Arrows show points of percussion, whereas solid lines represent places on a flake where thickness was measured.

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3. Interaction between platform depth and EPA: It has been suggested that flakes with large EPAs generally are large in size [91]. However, depending on the magnitude of platform depth flakes with large EPAs will be either thick with pronounced bulbs of percussion (observed at large values of platform depth) or will have a large surface areas (observed at small values of platform depth) [91,94]. In the course of bifacial reduction the bi-convex shape of the core–with necessarily acute edges–does not usually allow for large EPAs (>80°). This means that by default Mode 1 flakes will generally have more varied and larger EPAs than Mode 2. Importantly though, in comparison to Mode 1, the EPA values from Mode 2 flakes tend to be large relative to platform depth. In terms of multivariate statistics, the presence of a potentially significant interaction does *not* imply a correlation of two variables [100], it suggests that the effect of one influential variable on a response is not the same for all respective values of another influential variable. The interaction between platform depth and EPA was therefore included in the models formulated in this study.

4. Thickness evenness coefficient (Fig 3): This variable captures variation in flake thickness along the technological length axis. Thickness was measured at 25%, 50%, and 75% of the technological length. The standard deviation was then calculated for these three values. Low values indicate that thickness measurements do not vary greatly along the technological axis

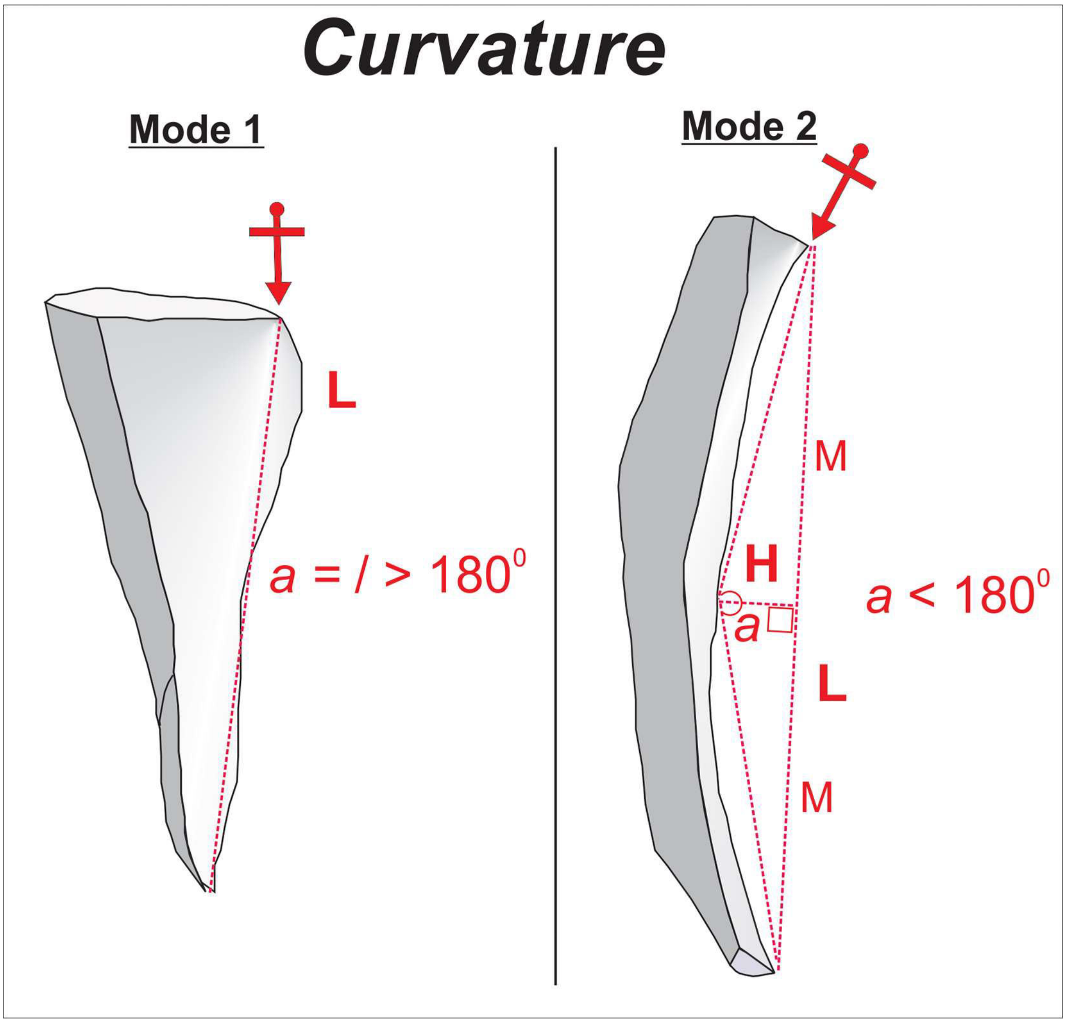

Fig 4. Curvature. Arrows represent points of percussion, dashed lines are the outlines of right triangles composed from the technological length and the height measurements.

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whereas high values indicate substantial variation in thickness along the technological axis. High values may be explained by flakes where the volume is concentrated at one point in the flake (e.g. bulb of percussion). Maintenance of the bi-convex section of an LCT requires removals with a relatively evenly distributed thickness, thus Mode 2 flakes are more likely to have lower values. Eren and Lycett [101] documented similar patterns of thickness variation within an individual flake in other technologies where flake shape is maintained by the knapper [101].

5. Interaction between platform depth and thickness evenness: The predictive capacity of one variable–may be augmented at either high or low values of the other variable. Therefore, the interaction between the two variables was included.

6. Curvature (Fig 4): The formula for calculating curvature on flakes was introduced by Andrefsky [102,103]; and here calculated on images of flake profiles using Image J 1.43u software (S1 Text). The curvature variable is based on predictions regarding how the morphology of a core surface is maintained. Core surface maintenance contingently affects the

shape of the flakes removed from it [95,104,105]. For example during *façonnage*, removals frequently invade beyond the midline of the plano-convex surface of an LCT [24]. Consequently, flakes associated with shaping tend to have curved profiles [63,102]. Since Mode 1 flakes are not associated with shaping of a form, they typically have either flatter profiles or convex ones due to the often pronounced character of the bulb.

Discriminant Function Analysis

Discriminant function analysis is a multivariate statistical technique that constructs linear functions which maximize separation between pre-existing groups [106,107]. The central principle of the discriminant function analysis is that linear combinations of the predictor variables are constructed in a way that between group variance is maximized [108]. Once the discriminant function is developed, using cases of known group classification, the classification of individual observations results in a probability of group affiliation [106]. A key utility of discriminant function analysis is that it enables classification of data that was not used to build the discriminant model. In this study, the model was built using the previously described experimental data set. This was followed by the classification of an out-group of experimental flakes to determine the number of flakes classified correctly. This cross validation methods serves to verify the discriminant function. Finally, archaeological flakes are classified using the same variables and then the discriminant function analysis produces a value that estimates the likelihood of group association.

The five predictor variables used in the development of the discriminant function analysis were EPA, platform depth (standardized by the geometric means of several size dependent variables), curvature, and thickness evenness (hereafter "test predictors"). Test predictors are included in the model as there is a specific question or hypothesis about them outlined in a study. On the contrary, the control predictors are not related to a specific hypothesis and are only considered in statistical models to monitor their potential effect [109]. Since we used quartzite and silcrete to create our experimental assemblage, in the model we included raw material as a control predictor. In this model, group membership (Mode 1 or Mode 2) of the flakes was the response. The number of whole flakes included in the test was 247.

As it has been already mentioned, platform depth was standardized with the geometric mean. The distributions of all predictor variables were checked for outliers, homogeneity of variances and the assumption of normality [110]. Consequently, platform depth and thickness evenness were transformed with a square root transformation to achieve distributions that approached the assumption of a normal distribution. To homogenize the predictors of different scales all covariates used in the model were standardized with the z-transformation which makes the covariate's mean equal 0 and standard deviation equal 1 [100]. Discriminant function analysis was performed R programing interface [111] using functions available in the "Mass" package, namely, 'lda' and 'lda predict' [112].

Generalized Linear Model

In addition to the discriminant function analysis we analyzed the data using the Generalized Linear Model with a binomial error structure and the logit link function [113]. We chose to use logistic regression as this enabled us to interrogate *how* the predictors (e.g. thickness evenness) operated and interacted with one another in distinguishing technological groups. The Generalized Linear Model was used to investigate how the predictors of curvature, platform depth, thickness evenness and EPA influenced group membership of Mode 1 and 2 flakes. Raw material was again added as a control predictor.

In our experimental assemblage there was a predominant use of flake blanks that retain only dorsal cortex (or remnants thereof) for LCT production. Mode 1 flakes were produced on cobbles as well as natural outcrops. Due to this necessary difference in blank forms used for Mode 1 and Mode 2 experimental assemblages, there was an uneven distribution of cortical and non-cortical flakes between the two groups. Cortex presence therefore potentially influences group membership as a response. In other words, Mode 1 flakes on aggregate tend to retain more cortex simply because there was more cortex present on the initial Mode 1 blanks used. Thus, we included cortex presence as another control predictor.

To verify the significance of the full model (the model where all predictors are included) we used a likelihood ratio test, comparing its deviance with that of the null model, which comprised of the intercept only. We tested for several interactions including (a) platform depth with EPA as well as (b) platform depth with thickness evenness. To test for the significance of these interactions we compared the full model's deviance with that of a corresponding reduced model comprising no interactions.

Overall, in the model (both the full model and the reduced model), we again used the platform depth variable standardized by the geometric mean to avoid size related effects. Similarly, to the discriminant function analysis, all covariates were again standardized with the z-transformation. All Generalized Linear Model variations derived in this study were checked for a series of assumptions regarding data distribution and model stability including collinearity, DfBetas, leverage and overdispersion [110,114–116]. The model was fitted in R [111], using the "glm" function.

Results

Discriminant Function Analysis

The discriminant function analysis resulted in an 87.4% success rate in experimental flake classification (Fig 5). A subsequent analysis with jackknife re-sampling, a cross validation method of leaving one observation out [108], resulted in a similar percentage of correctly classified cases. The jackknife method prevents a situation where the model is tested against the same specimens that are used to create the model.

As raw material type was identified as a significant predictor (Table 3), we considered the percentage of correctly classified cases using a subset of the data that included only silcrete flakes (therefore raw material variability was removed as a predictor). In that data subset the percentage of correctly classified classes is 84% and when using jackknife re-sampling 82% of specimens were correctly classified. Therefore, with and without the inclusion of raw material variation, the standardized coefficients of the linear discriminants show extremely similar results. In the dataset where the raw material is not included the effect sizes of the individual predictors is the following: the curvature variable plays the most prominent role in separating the technological groups followed by thickness evenness, EPA and platform depth (Table 4).

Generalized Linear Model

A likelihood ratio test comparing the null and the full Generalized Linear Model was highly significant ($\chi^2 = 225$, df = 7, $P < 0.001$) (Table 5). The reduced model that did not include interactions revealed that curvature, thickness evenness, platform depth and EPA were all significant predictors (see Table 6 for coefficients). There was a significant interaction between thickness evenness and platform depth. The likelihood ratio test comparing the reduced (no interaction) and full models was also highly significant ($\chi^2 = 239$, df = 1, $P < 0.01$). The significance of the

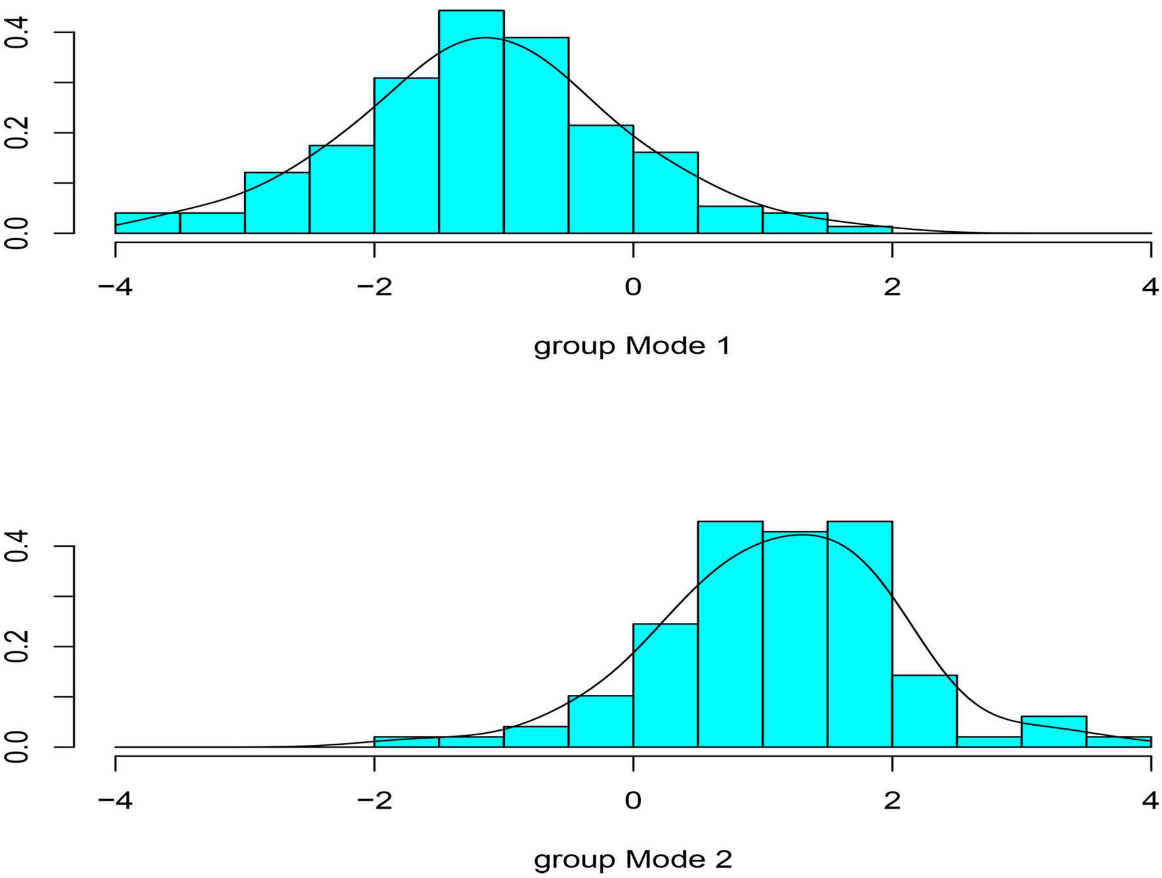

Fig 5. Discriminant function analysis-Experimental. A histogram showing the results of the discriminant function scores with the inclusion of experimental data only.

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interaction implies that at greater platform depths, thickness evenness has a greater impact on the separation of whole flakes in Mode 1 and Mode 2 groups (Fig 6). As raw material was a significant predictor, we tested the model holding raw-material constant. Table 7 shows the result of the data subset that includes only the silcrete assemblage. The effect sizes and significance of the individual predictors is similar.

The percentage of dorsal cortex was also a significant predictor. To isolate the effect of cortex as a predictor, we formulated an additional model that incorporated only non-cortical flakes from the experimental assemblage. Table 8 shows the data subset that includes only non-cortical flakes. In this model, our test variables (platform depth, thickness evenness, curvature

Table 3. The results of the discriminant function analysis on experimental assemblage showing the loadings of the linear discriminant 1.

	LD
Raw material	1.02
Curvature	-0.78
Thickness even.	-0.51
EPA	0.33
Platform depth	-0.19

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Table 4. The data subset showing the loadings of the liner discriminant 1 for only those experimental flakes made on silcrete.

	LD
Curvature	-0.79
Thickness even.	-0.72
EPA	0.24
Platform depth	-0.21

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and EPA) show similar patterns to the model that included both cortical and non-cortical flakes.

Discriminant function analysis: predicting archaeological flake group association

The whole flakes from Elandsfontein Cutting 10 were classified into Mode 1 (68%) and Mode2 (32%) using the experimental linear discriminant model in its predictive capacity (Fig 7). The posterior probabilities measure the strength of association of each specimen to a specific technological group membership. If the posterior probability is closer to 1 it means that a specimen was confidently assigned to either Mode 1 or Mode 2 group [108]. In our study the majority of archaeological flakes had posterior probabilities that were between 0.8 and 0.9 and the mean of posterior probabilities for the archaeological flakes was equal to 0.8 (sd = 0.2). This suggests that most archaeological flakes were confidently assigned to a given group. Ten out of eleven archaeological flakes classified as Mode 2 were made on silcrete. Only one of the quartz flakes was classified as Mode 2. The majority of the Elandsfontein Cutting 10 flakes (79%) used in our analysis are made on silcrete. Interestingly this contrasts with the high frequency of LCTs made on an igneous rock.

Table 5. The results of the Generalized Linear Model (group~ plat.depth*thick. eve. +epa + curvature+ cortex+ raw material) on experimental assemblage.

Effect (2)	Estimate	SE	t	P	lower CI	upper CI
Intercept	-1.264	0.351	(1)	(1)	-2.019	-0.624
platform depth (3), (4)	-0.330	0.288	(1)	(1)	-0.911	0.229
thickness evenness	-1.919	0.436	(1)	(1)	-2.895	-1.149
Curvature	-1.955	0.396	-4.934	0.000	-2.804	-1.237
Epa	-0.895	0.358	-2.502	0.012	-1.655	-0.236
Cortex	-2.053	0.877	-2.339	0.019	-3.865	-0.410
raw material	2.378	0.685	3.472	0.001	1.117	3.830
plat. dp:thick. eve	1.068	0.398	2.682	0.007	0.307	1.907

(1) not shown because of not having any meaningful interpretation

(2) all covariates were z-transformed to a mean = 0 and sd = 1, original means (sd) were: curvature: 175.67(10.61); epa: 68.46(14.90); thickness evenness: 2.71 (2.18); platform depth: 10.53(6.82)

(3) square root transformed prior to z-transformation

(4) standardized by the geomean

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Table 6. The results of the reduced Generalized Linear Model, with no interactions.

Effect [2]	Estimate	SE	t	P	lower CI	upper CI
Intercept	-1.097	0.330	[1]	[1]	-1.791	-0.488
platform depth [3], [4]	-0.691	0.250	-2.760	0.006	-1.214	-0.218
thickness evenness	-1.837	0.415	-4.422	0.000	-2.724	-1.078
Curvature	-1.697	0.350	-4.855	0.000	-2.441	-1.057
Epa	-0.885	0.329	-2.689	0.007	-1.580	-0.277
Cortex	-1.661	0.799	-2.080	0.038	-3.311	-0.159
raw material	2.121	0.637	3.330	0.001	0.938	3.466

(1) not shown because of not having any meaningful interpretation

(2) all covariates were z-transformed to a mean = 0 and sd = 1, original means (sd) were: curvature: 175.67(10.61); epa: 68.46(14.90); thickness evenness: 2.71 (2.18); platform depth: 10.53(6.82)

(3) square root transformed prior to z-transformation

(4) standardized by the geometric mean

doi:10.1371/journal.pone.0130732.t006

Discussion and Conclusion

Influential variables (test predictors) and their association with shaping

The objective of this paper was to quantify and explore the key morphological variables that distinguish between flakes produced during Mode 1 and Mode 2 core reduction. The results of both the discriminant function analysis and Generalized Linear Model demonstrate that curvature and thickness evenness are the most important factors in determining the technological attribution of the archaeological and experimental flakes.

Fig 8 plots group association as a logistic function of curvature at the average values of all other variables (which, as described previously were z-transformed). The plot demonstrates that the Generalized Linear Model fits the experimentally derived data exceptionally well. As the curvature variable is associated with an angle, low values represent flakes that are very curved. Low values for the curvature variable are associated with the Mode 2 group and high values are associated with the Mode 1 group. The inflection point lies between 160 and 180 degrees (Fig 8).

The relative effect of the curvature variable is associated with marked differences in the morphology of the core surfaces from which the flakes were removed. Plano-convex and bi-convex bifacial cores [24] are strikingly different from the cross-sectional shape of the Mode 1 cores. These differences are associated with whole flake profiles from bifacial tool production that are more curved (i.e. low angles in the present study) and less curved Mode 1 flakes (angles larger than 160 in the present study).

In contrast, although EPA was a statistically significant predictor in the Generalized Linear Model, it has a notably smaller effect on the response (Tables 4 and 6). Fig 9 shows a model based on EPA at the average values of all other predictors. The fitted model does not explain the error distribution in the EPA data well, particularly where values of Mode 1 flakes are displayed on the graph. This result might be explained by the fact that EPA is influential in differentiating Mode 1 and 2 techniques only while interacting with platform depth. However, the interaction between EPA and platform depth was not significant as the comparison between the full model (with the interaction) and the reduced model (without interaction) revealed: $\chi^2 = 239$, df = 1, P> 0.05.

Thickness evenness and platform depth played an important role in the discriminant function analysis and Generalized Linear Models as individual predictors (Tables 4 and 6).

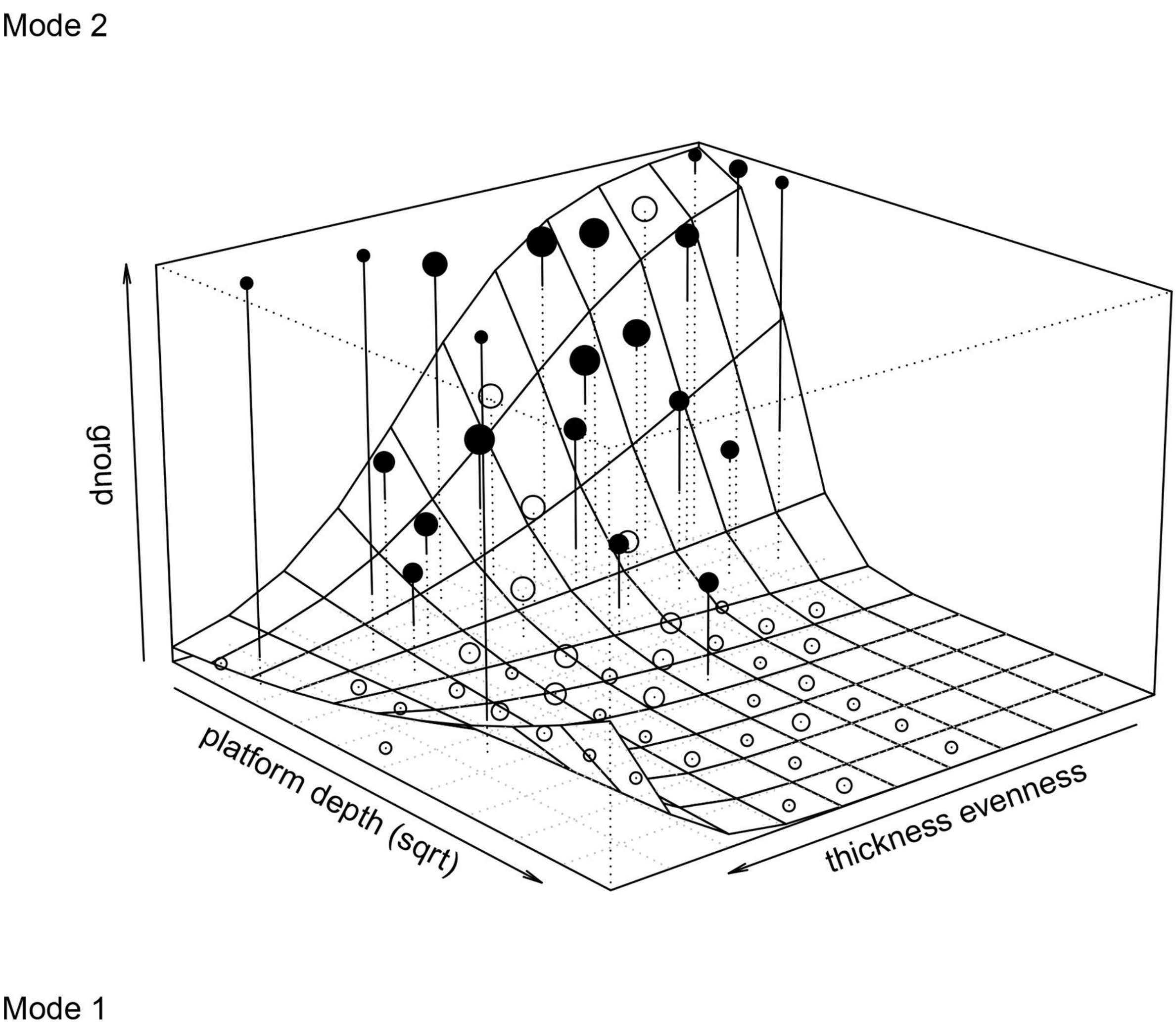

Fig 6. Generalized Linear Model-Platform depth * thickness evenness. The plot represents the effect of platform depth and thickness evenness on group separation at the average of EPA, curvature and raw materials. Points depicting the average response per cell of the fitted surface can be scaled according to the number of data in the respective cell and are depicted as filled when the average is above the fitted model and as open points when they are below. Points are connected to the bottom of the figure by a line, which is dashed between the bottom of the figure and the fitted surface, and solid above it.

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However, most importantly the interaction tested in the Generalized Linear Model between thickness evenness and platform depth proved to be significant. Fig 6 is a three-dimensional plot depicting platform depth, thickness evenness and group membership on y, x and z axes respectively. Overall, there is a good fit between the data and the model.

The plot reflects the interaction between thickness evenness and platform depth, which is critical in separating technological groups. For flakes with low thickness-evenness values–'even' flakes in terms of how thickness is distributed along the length axes—platform size is a relatively good predictor of technological group membership. However as flakes become progressively more uneven and thickness-evenness values increase, platform size is far less decisive—to not being influential at all—in determining whether flakes are associated with Mode 1 or Mode 2 groups. This means, for example, that the predictive strength of the platform depth variable for a given flake is dependent on the values of the thickness evenness variable for that flake.

Table 7. The results of the Generalized Linear Model including only silcrete flakes (n = 170).

Effect(2)	Estimate	SE	t	P	lower CI	upper CI
Intercept	0.357	0.363	(1)	(1)	-0.371	1.076
platform depth (3), (4)	-0.418	0.299	(1)	(1)	-1.035	0.152
thickness evenness	-2.049	0.488	(1)	(1)	-3.174	-1.211
Curvature	-2.046	0.456	-4.4853	0.000	-3.040	-1.231
Epa	-1.167	0.425	-2.7472	0.006	-2.093	-0.401
Cortex	-2.328	1.018	-2.2869	0.022	-4.429	-0.388
plat. depth:thick. eve	1.144	0.429	2.66522	0.008	0.348	2.072

(1) not shown because of not having any meaningful interpretation

(2) all covariates were z-transformed to a mean = 0 and sd = 1, original means (sd) were: curvature: 173.69(10.99); epa: 65.23(15.35); thickness evenness: 2.42 (2.07); platform depth: 8.44(5.57)

(3) square root transformed prior to z-transformation

(4) standardized by the geometric mean

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The significance of the described interaction between thickness evenness and platform depth has implications for the identification of bifacial shaping in the archaeological record. Identifying flakes resulting from bifacial shaping is difficult when looking only at the main *effects* of *individual* morphological variables. Understanding the combined effects of some of these variables is critical in this endeavor. Combined effects–or interactions–make distinguishing bifacial products from flake and core technologies highly complex. The Generalized Linear Model was therefore critical here in that it enabled us to investigate how different aspects of flake morphology behave relative to one another within each technological group. Further, these relationships influence the situations in which certain variables can be accurately used to identify flake production strategies.

Application to the archaeological materials

Singer & Wymer [34] and later Deacon [33] suggested that LCTs at Elandsfontein Cutting 10 were probably not made on site. Further, they proposed that flakes recovered at this locality

Table 8. Table shows the results of the Generalized Linear Model including only non-cortical flakes (n = 198).

Effect(2)	Estimate	SE	t	P	lower CI	upper CI
Intercept	-2.938	0.778	(1)	(1)	-4.619	-1.538
platform depth (3), (4)	-0.247	0.322	(1)	(1)	-0.899	0.371
thickness evenness	-2.585	0.638	(1)	(1)	-4.055	-1.531
Curvature	-2.198	0.480	-4.577	0.000	-3.251	-1.347
Epa	-1.126	0.424	-2.656	0.008	-2.042	-0.355
raw material	2.561	0.791	3.238	0.001	1.116	4.253
plat. depth:thick. eve	1.484	0.522	2.844	0.004	0.536	2.620

(1) not shown because of not having any meaningful interpretation

(2) all covariates were z-transformed to a mean = 0 and sd = 1, original means (sd) were: curvature: 175.13(10.76); epa: 67.26(15.02); thickness evenness: 2.53 (2.18); platform depth: 9.67(6.68)

(3) square root transformed prior to z-transformation

(4) standardized by the geomean

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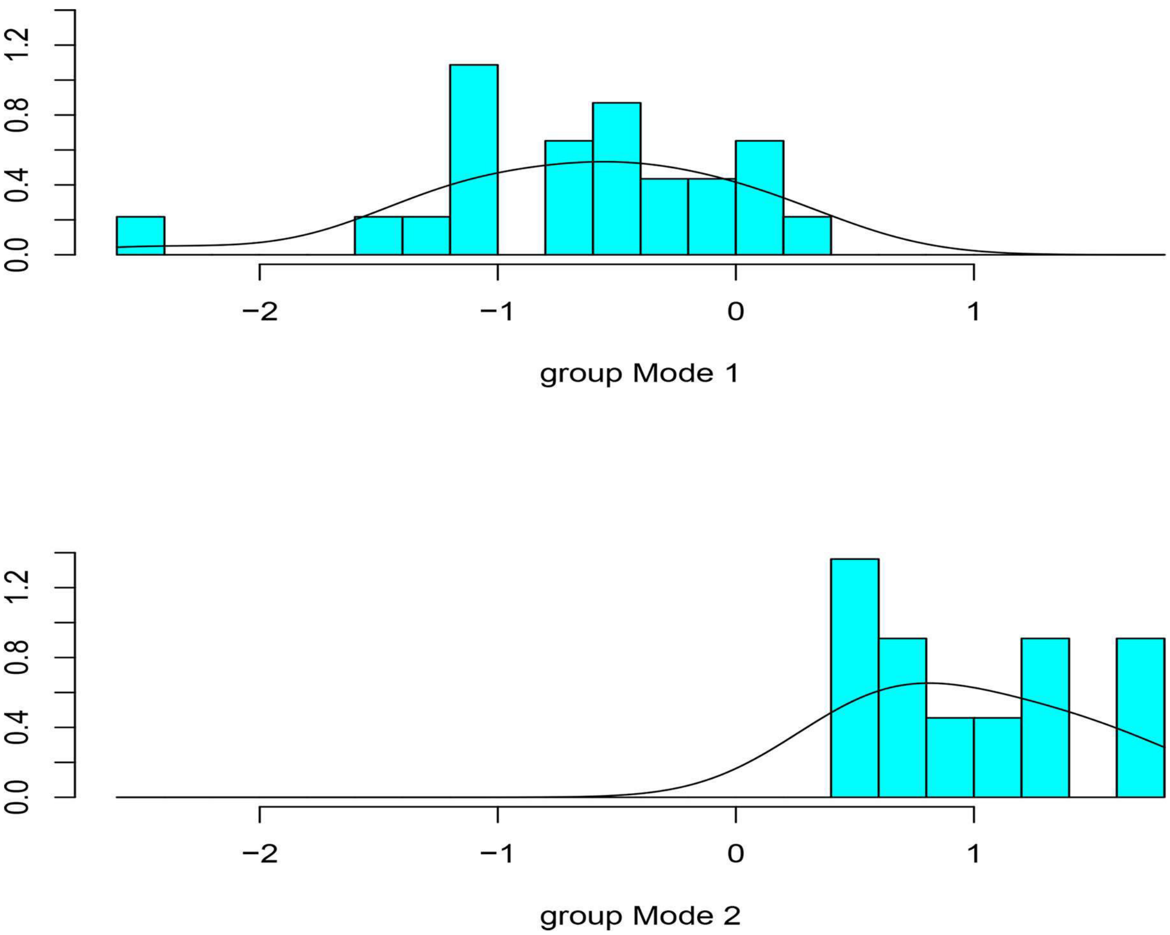

Fig 7. The classification of archaeological material. Histogram showing the results of classifying Elandsfontein Cutting 10 using the discriminant function analysis model built with the experimental dataset.

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were unlikely to be related to the production of LCTs. These suggestions were made based on typological and descriptive observations of the assemblage.

Our quantitative study supports this finding by demonstrating that the majority of flakes in the assemblage are the products of Mode 1 like technological strategies. Our findings confirm the suggestion that the LCTs were indeed made elsewhere and transported to the Elandsfontein Cutting 10 locality in their reduced form. Even though the majority of the flake collection are products of Mode 1 strategies, the proportion of Mode 1 to Mode 2 cores in the collection is slightly smaller (49% are Mode 1 cores, 51% Mode 2 bifacial pieces).

Moreover, 62.5% of the LCTs from Cutting 10 were made on quartz porphyry (27% made on silcrete, and 10.5% made from quartz) while 91% of those archaeological flakes assigned by the discriminant function analysis to Mode 2 were made on silcrete. The absence of quartz porphyry flakes also suggests that LCTs made on this raw material were manufactured and maintained away from the site. In contrast, based on (1) the absence of LCT blanks or preforms, and (2) the presence of Mode 2 silcrete flakes we propose that silcrete LCTs were manufactured away from Cutting 10, but underwent some maintenance at the Cutting 10 locality.

Overall, our analysis indicates the presence of two distinct technological strategies practiced at the Cutting 10 locality. One strategy entails the onsite reduction and discard of Mode 1 cores along with their associated *debitage*. The second strategy is represented by LCT forms, which

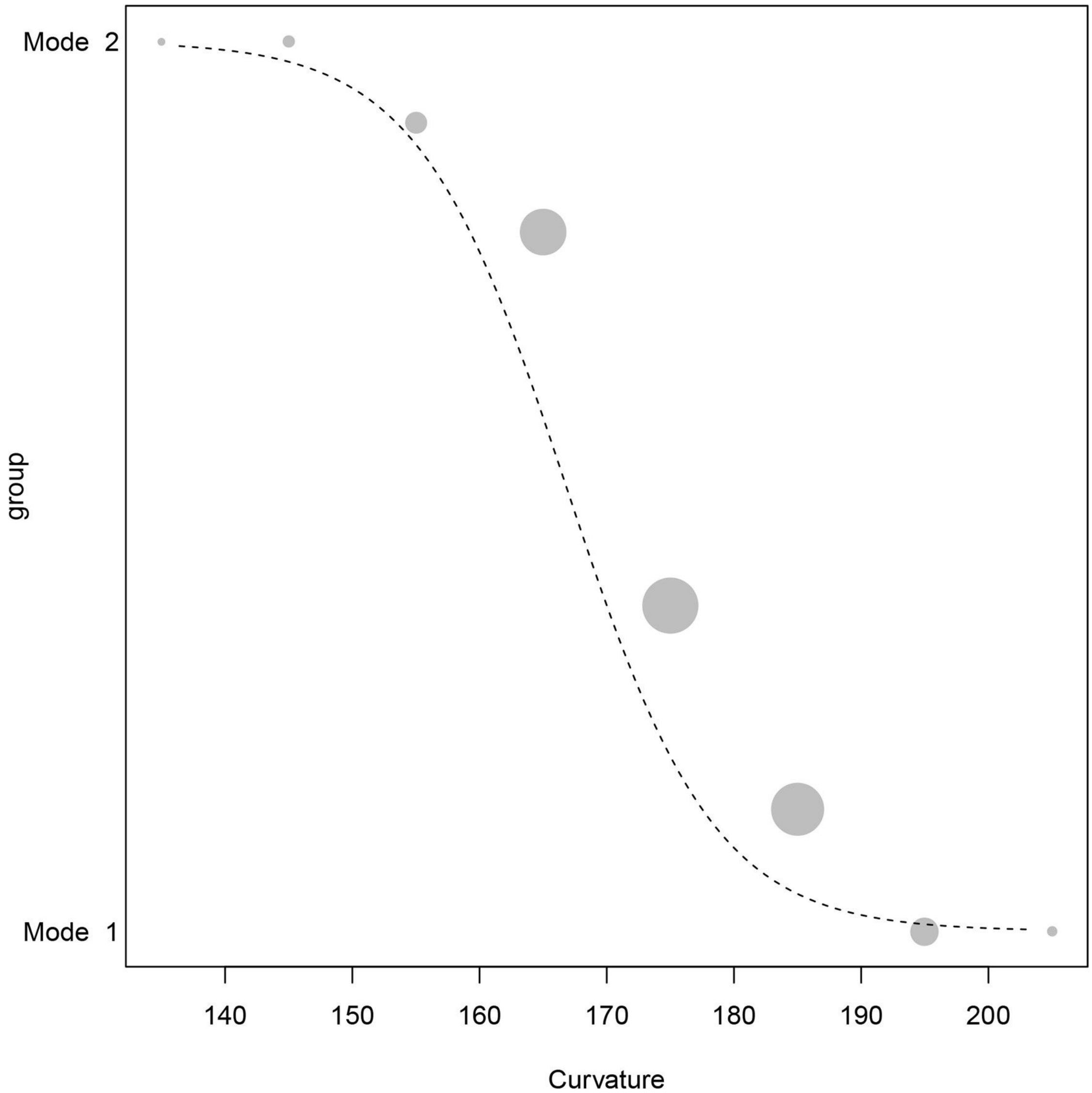

Fig 8. Generalized Linear Model-Curvature. The graph depicts the group association probability as a function of curvature. The dashed line is the fitted model. For visual clarity, curvature was binned in 10 degree sections. The area of the circles corresponds to the sample size per cell. The binned curvature values—which have different areas based on the sample represented—are concentrated between 160 and 170 degrees.

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were transported to the site in a reduced state and then discarded. This suggests that hominins at Elandsfontein Cutting 10 varied decisions regarding the discard and maintenance of the products of different technological systems based on different contextual factors. Current analyses are ongoing in the reconstruction of these contextual factors [117].

Reviews of the time period when the Acheulean first appeared often suggest that Mode 2 technology rapidly replaced Mode 1 technology shortly after the appearance of the Acheulean in the Early Pleistocene [38,73,118]. However, the Elandsfontein Cutting 10 example indicates the importance of Mode 1 cores even in assemblages where the counts of LCTs and cores suggest that LCT production is the major component of the technological strategy. This further supports the assertion that cores/LCTs and detached pieces may reflect subtly different

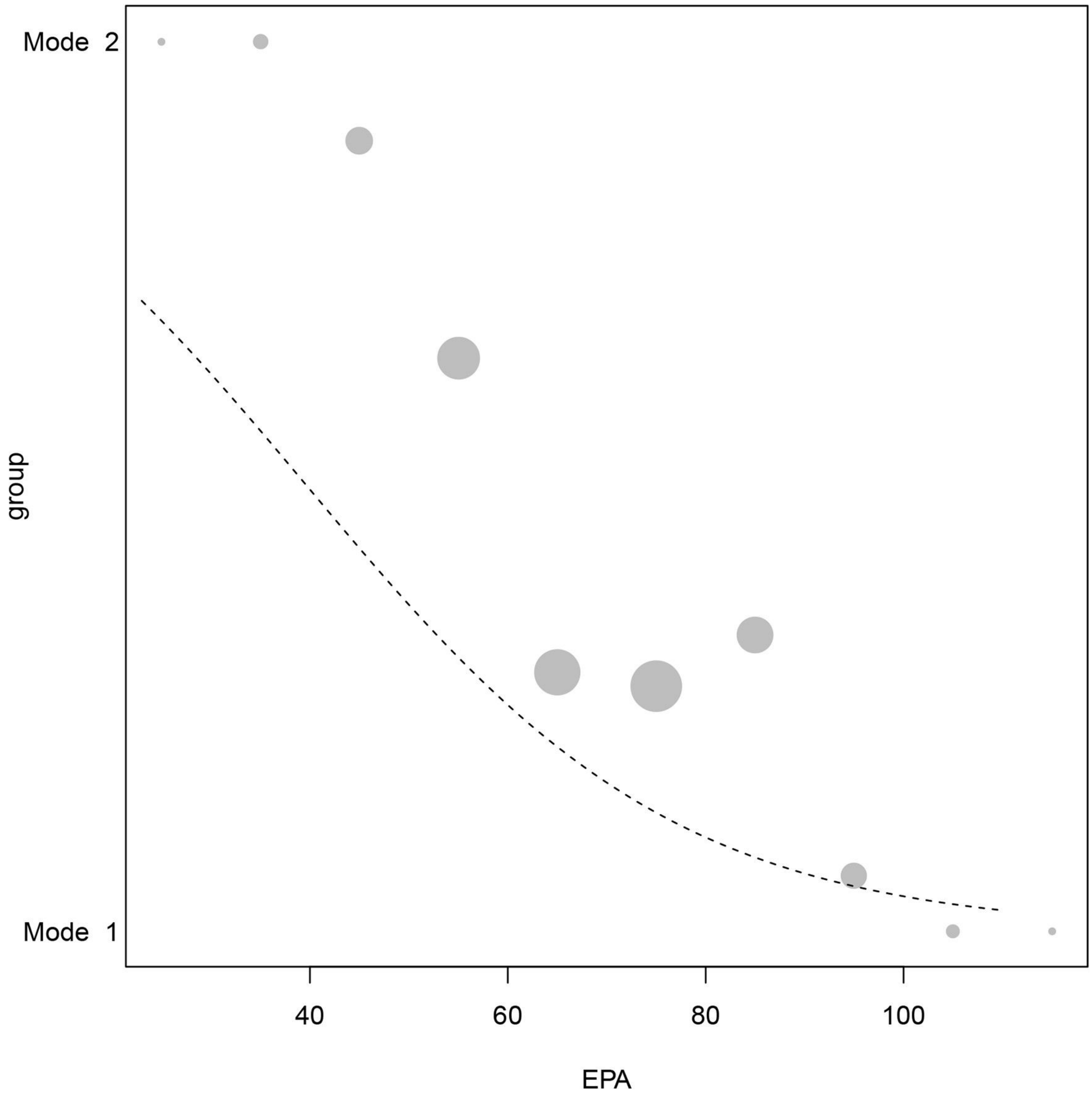

Fig 9. Generalized Linear Model-EPA. The graph depicts the group association probability as a function of EPA. The dashed line is the fitted model. For visual clarity, curvature was binned into 10 degree sections. The area of the circles corresponds to the sample size.

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components of a technological system, and perhaps underpin different aspects of hominin tool transport behavior [119]. This suggests that complex and variable behavioral factors may be elucidated by distinguishing Early Stone Age technological systems based on the characteristics of both flake and core assemblage components, and the discussion of quantitatively determined frequencies in this regard.

The rare agreement between this study and previous–methodologically different—independent avenues of investigation [33,34] further validates the results of our analyses. Additionally this agreement suggests that the methodology we present here may be useful in the investigation of other Pleistocene assemblages where traditionally characteristic cores are absent.

Supporting Information

S1 Table. Raw material percentages. Raw materials used in experimental and archaeological assemblages.
(DOCX)

S2 Table. Archaeological assemblage.
(XLSX)

S3 Table. Experimental assemblage.
(XLSX)

S1 Text. Supporting text: Measurements of the curvature variable.
(DOCX)

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Author Contributions

Conceived and designed the experiments: DP WA DRB WF. Performed the experiments: DP WA DRB WF. Analyzed the data: DP WA DRB WF. Contributed reagents/materials/analysis tools: DP WA DRB WF. Wrote the paper: DP WA DRB WF.

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Appendix II.

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Site fragmentation, hominin mobility and LCT variability reflected in the early Acheulean record of the Okote Member, at Koobi Fora, Kenya

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ABSTRACT

From its initial appearance at ~1.7 Ma, the Acheulean was prevalent through a vast chronological span of hominin behavioural evolution that lasted nearly 1.5 million years. The origins and production patterns of large bifacial cutting tools ('LCTs') — the marker of the Acheulean techno-complex — and the systematic changes in this behaviour through time are gaining increasing interest in paleoanthropology. Here we provide a synthesis of early Acheulean LCT variation in a landscape context by analysing assemblages from four different quasi-contemporaneous (~1.4 Ma) sites from the Koobi Fora Formation. We characterize this variation using both 3D geometric morphometric and descriptive approaches. The expansive lateral exposures of fluvial and lacustrine sediments, as well as the associated tephrostratigraphy of the Koobi Fora Formation provide the landscape context that enables these comparative analyses. Our study demonstrates that when multiple contemporaneous early Acheulean localities are analysed together, a broader picture of LCT variability is elucidated. Four sites at Koobi Fora appear to represent a single system of lithic economy, characterized by a discrete trajectory of changes in LCT size and shape. These sites have ranges of LCT forms which appear to represent different but overlapping stages on a single reduction trajectory. Certain sites exhibit the full reduction trajectory while others exhibit only fragments of this trajectory. Other inter-site lithic proxies further complement these patterns in LCT variability. We explore patterns of site function, mobility and hominin landscape use, all of which may be suggestive of a depth of planning in early Acheulean hominins wherein technological activities were undertaken in substantial anticipation of future needs.

1. Introduction

The origins of the Acheulean techno-complex, and the hominin behavioural transition to the systematic production of large, standardized bifacial cutting tools is gaining increasing interest in palaeoanthropology. The dawn of Acheulean technology is associated with the onset of a growing number of varied hominin behavioural innovations (Lepre et al., 2011; Beyene et al., 2013). These include the expansion of hominin foraging ranges, increases in the efficiency of stone raw material procurement, consumption and use, increased depths of planning and organization in stone tool production and a clear ability to integrate design templates into stone tool production (Hay, 1976; Isaac, 1977; Gowlett, 1984; White, 1995; Feblot-Augustins, 1997; Potts et al., 1999; Braun and Harris, 2003; Sampson, 2006; Braun et al., 2009c; de la Torre, 2016). African Acheulean research has tended to place primacy on documenting the antiquity of large bifacial cutting tool related behaviours in the record, rather than some of these broader features of the Acheulean behavioural system. The landscape variability of Acheulean behaviour between spatially separated early Acheulean sites has received little attention (yet see Potts et al., 1999; de la

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Torre et al., 2014). However, a better understanding of the adaptive variability of the Acheulean partially relies on 1) how spatially separated assemblages relate to one another, and 2) in what ways technology varied spatially relative to landscape and resource variability.

The earliest appearance of Acheulean technology in the archaeological record has been documented at ~1.76 Ma, at the sites of Kokiselei in West Turkana, Kenya and at Konso-Gardula in southern Ethiopia (Lepre et al., 2011; Beyene et al., 2013). The broader period from the early to middle Pleistocene in eastern Africa, within which the Acheulean emerged, is characterized by marked changes towards generally drier, yet more variable climate with rapid shifts between wetter and drier conditions, expansions of grassland adapted mammals, and the emergence of *Homo erectus* ~1.89 Ma (Rightmire, 1991; Bobe and Behrensmeyer, 2004; DeMenocal, 2004, 2011; Maslin and Christensen, 2007; Trauth et al., 2007; Antón, 2012; Antón et al., 2014; Levin, 2015; Patterson et al., 2017). Interactions between environmental context and hominin biological change are likely to have been mediated by co-occurring innovations in subsistence related behaviours, such as the adoption by hominins of new technological systems (Foley and Lahr, 2003; DeMenocal, 2004; Lepre et al., 2011; Potts and Faith, 2015). However, the nature of the potential feedback between hominin behavioural and biological change in the framework of the emergence of the first Acheulean technologies remains highly ambiguous (Braun, 2015). Detailed investigation of how the first Acheulean technologies varied spatially, relative to an associated landscape-scale resource framework, will expand our understanding of the adaptive variability of this techno-complex.

Much of the research on Acheulean assemblages older than 1 Ma has focused relatively exclusively on documenting the initial presence, onset and diachronic variability of this technological system (Roche et al., 2003; de la Torre and Mora, 2005; de la Torre et al., 2008; Lepre et al., 2011; de la Torre, 2011, 2016; Beyene et al., 2013; Gallotti, 2013; Diez-Martín et al., 2014, 2015; Gallotti and Mussi, 2017). Important gaps in our understanding of this earlier stage of the Acheulean are that it is unclear 1) how much technological variability one could expect to see within this complex across a relatively short time frame, 2) to what degree variability in the life histories of Acheulean tools explains broader patterns of technological/morphological diversity, and 3) how different landscape contexts influence variability in Acheulean tool forms.

In this contribution, we address four questions. 1) Did large cutting tools (hereafter LCTs), the 'fossile directeurs' of the early Acheulean technological system (Inizan et al., 1999), vary substantially in terms of shape, size, and technology between and within early Acheulean sites at Koobi Fora? 2) Was a standardized strategy used for LCT production in early Acheulean assemblages from the Koobi Fora Formation? 3) If documented, what behavioural factor(s) explain morphological variability within contemporaneous early Acheulean assemblages? 4) What does LCT morphological and technological variability tell us about hominin landscape use?

This study provides the first combination of descriptive and morphometric analyses of artefacts from four broadly contemporaneous early Acheulean sites at Koobi Fora dated to ~1.4 Ma. These four sites — FxJj65, FxJj63, FxJj37 and FxJj21 — represent the best-documented sites attributed to the early Acheulean from the Koobi Fora Formation (Isaac and Harris, 1997). We investigate the behavioural patterns underpinning artefact variability through 3-dimensional geometric morphometric analysis (3DGM) of artefact size and shape. The use of 3DGM and experimental data enables us to gain insight onto allometric trajectories in relatively large assemblages of early Acheulean LCTs. Documenting variation in three-dimensional shape relative to size in an assemblage allows one to evaluate which shapes were consistently produced by past hominins, whilst not making any assumptions about what aspects of LCT shape were important to the LCT manufacturer. In addition we are able to document how different patterns of allometric change map out in LCTs produced in spatially separated locations in the early Acheulean at Koobi Fora. Descriptive analysis provides insight onto the central aims of production within the lithic chaînes opératoires present in these assemblages (Roche and Lefevre, 1988; Boëda et al., 1990; Geneste, 1991; Pelegrin, 1993; Inizan et al., 1999). The 3DGM and descriptive approaches serve as independent but complimentary avenues of analysis, and facilitate interpretation of the complex geometric morphometric patterns in a behavioural context.

2. Background

2.1. Early Acheulean definition and characteristics

Early Acheulean sites and assemblages are distinguished from later Acheulean sites largely by the paucity of bifacially and bilaterally symmetrical LCT forms (Inizan et al., 1999). Although not entirely absent, these highly symmetrical bifacial pieces are rare within early Acheulean assemblages (Leakey, 1951, 1957, 1971, 1976; Kleindienst, 1962; Gowlett, 1986; de la Torre and Mora, 2005; Beyene et al., 2013). As a consequence of this compositional difference, Stout (2011) proposed the term 'early Acheulean' in an attempt to separate later Acheulean assemblages from the earlier sub-stages of the Acheulean techno-complex. Stout (2011) argued that LCTs older than 1 Ma are representative of a substantially simpler sequence of actions during the manufacture process, compared to the often complex 'chaîne opératoire' of LCTs younger than 1 Ma (Roche, 2005; Beaumont and Vogel, 2006). Following Stout, we adopt the term 'early Acheulean' to refer to the collections analysed within this study.

The vast majority of known early Acheulean sites have been documented in eastern Africa and in the Vaal River gravels of South Africa (Table 1) (Ludwig and Harris, 1998; Kuman and Clarke, 2000; Quade et al., 2004; de la Torre and Mora, 2005; de la Torre et al., 2008; Gibbon et al., 2009; Lepre et al., 2011; Beyene et al., 2013; Diez-Martín et al., 2015; Leader et al., 2016). The available literature reporting on these analyses (Table 1) suggests broadly that early Acheulean LCTs share a number of key characteristics. First, these LCTs tend to be made on large flake blanks (>10 cm in maximum dimension) and are often unifacial. The dorsal surface of the large flake blank was used regularly as the primary knapping surface. The ventral surface of the blank generally served as the knapping platform. This organization of knapping surface hierarchy associated with flake blank use, often resulted in LCTs which were unifacial. Examples of this organization have been described at many early Acheulean sites such as EF-HR at Olduvai (de la Torre and Mora, 2005), Peninj (de la Torre et al., 2008), FxJj63 at Koobi Fora (Ludwig and Harris, 1998), Gadeb 8F (de la Torre, 2011), KGA6-A1 at Konso-Gardula (Beyene et al., 2013) and Rietputs 15 from the Vaal River (Li et al., 2016; Kuman and Gibbon, 2017).

Second, flake removal sequences on early Acheulean LCTs tend to be limited (few sequential removals in an individual removal series), and usually are non-invasive or 'marginal'. Flake scars rarely extend beyond 50% of the width of a flaked piece. As a consequence of these removal characteristics, the shaping removals tend not to create bifacial or bilateral symmetry on the pieces being shaped. Examples of such LCT asymmetry in association with these kinds of non-invasive removals are evident at EF-HR, TK and FLK West at Olduvai Gorge (de la Torre and Mora, 2005; Diez-Martín et al., 2015), KGA6-A1 at Konso Gardula (De Lumley and Beyene, 2004; Beyene et al., 2013), Kokiselei 4 in West Turkana (Roche et al.,

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Table 1
List of early Acheulean (older than 1 Ma) sites in Africa with list of features described as being characteristic of these assemblages.[a]

Area	Site	Age (Ma)	Basic LCT features
West Turkana	Kokiselei 4	~1.76	LCT blanks: split cobbles; bifacial and unifacial LCTs; non-invasive removals
	Kokiselei 5	~1.65	Small to medium flake production; a single LCT
Konso Gardula	KGA6-A1	~1.75	LCT blanks: large flakes; majority of LCTs unifacial (dorsal surface reduction), non-invasive removals; hierarchical organization of LCT surfaces (hereafter HOS); highly asymmetric pieces
	KGA4-A2	~1.6	LCT blanks: large flakes; majority of LCTs bifacial; alternate bifacial reduction
	KGA10-A11	~1.45	Majority of LCTs bifacially reduced
	KGA7-A1, A2, A3	~1.4	Majority of LCTs bifacially reduced
	KGA12-A1	~1.25	Majority of LCTs bifacially reduced; unusually invasive sequences of removals; a number of refined pieces
Gona	OGS-5	1.6	LCT blanks: Large flakes
	OGS-12	~1.6	LCT blanks: Large flakes
Olduvai Gorge	FLK-West	~1.7	LCT blanks: large flake blanks, and tabular clast blanks; majority of LCTs bifacially worked; non-invasive removals; highly asymmetric pieces
	EF-HR	~1.5–1.4	LCT blanks: large flakes; majority of LCTs unifacial (dorsal surface reduction); non-invasive removals; highly asymmetric pieces; HOS
	TK	~1.5–1.33	LCT blanks: split cobbles/large blocks; mostly bifacial; non-invasive removals
	BK	~1.33	Bifacial LCTs; invasive removals; symmetric pieces
Nyabusosi	Nyabusosi	~1.5	no LCTs; possibly shaping flakes
Koobi Fora	FxJj63[b]	~1.4	LCT blanks: flakes; invasive removals
	FxJj37[b]	~1.4	LCT blanks: flakes; sometimes bifacial LCTs
Peninj	ST-Complex	~1.6–1.4	no LCTs; possibly shaping flakes
	RHS-Mugulud	~1.5–1.4	LCT blanks: large flakes; mostly unifacial pieces(dorsal surface reduction); non-invasive removals; HOS
	MHS-Bayasi	~1.5–1.4	LCT blanks: large flakes; mostly unifacial pieces(dorsal surface reduction); non-invasive removals; HOS
Gadeb	Gadeb 8E, 8F	~1.4–0.7	LCT blanks: cobbles and flakes; mostly non-invasive removals; some bifacial and symmetrical LCTs
Melka Kunture	Garba IVD	~1.5	LCT blanks: flakes; unifacial and bifacial pieces; non-invasive removals
	Garba XIIIB	~1	LCT blanks: large flakes; majority bifacial LCTs; invasive removals
Sterkfontein	Member 5	~1.7–1.4	LCT blanks: flakes and cobbles; crude LCTs
Swartkrans	Member 2	~1.5	LCT blanks: flakes and cobbles; bifacial and unifacial pieces; non-invasive removals; only a few LCTs
Vaal River	Rietputs 15	~1.3–1.27	LCT blanks: flakes and cobbles; bifacial and unifacial pieces; non-invasive removals; non symmetrical pieces; HOS

[a] Data from Isaac, 1965, 1967; Leakey, 1971; Clark and Kurashina, 1976, 1979; Clark, 1987; Brain et al., 1988; Texier, 1995; Harris and Isaac, 1997; Kuman and Clarke, 2000; Quade et al., 2004; de la Torre and Mora, 2005; Kuman, 2007; de la Torre et al., 2008; Gibbon et al., 2009; Lepre et al., 2011; de la Torre, 2011; Beyene et al., 2013; Gallotti, 2013; Diez-Martín et al., 2014; Leader et al., 2016.
[b] The description of FxJj37 and FxJj63 in the table is taken from Harris and Isaac (1997).

2003), Vaal River sites (Leader, 2009; Leader et al., 2016; Kuman and Gibbon, 2017), and Garba IV at Melka Kunture (Gallotti, 2013).

Not all assemblages share all of these defining characteristics. Early Acheulean sites tend to exhibit variable combinations or mosaics of these features. For instance, certain early Acheulean LCT collections appear to exhibit only one of these features, such as FxJj63 in East Turkana, Kenya, where Ludwig and Harris (1998) reported on a small number of unifacial LCTs that were made on flake blanks, but which were intensively reduced with invasive and longer sequences of removals. Importantly, a small number of proposed early Acheulean sites exist that are entirely lacking in any of the above-mentioned characteristics, such as the BK site at Olduvai Gorge (de la Torre and Mora, 2005). The relatively younger locality of KGA12-A1 from Konso Gardula also does not exhibit these patterns (Beyene et al., 2013). Both sites appear to have a small number of intensively reduced and refined LCTs. Further, a small number of proposed early Acheulean sites contain LCTs that have the above-mentioned key technological features (use of flake blanks, hierarchical surface organization and marginal removal extent/intensity) in addition to a relatively smaller number of more symmetrical finely shaped LCTs. One example of this mosaic of early and later Acheulean characteristic features is the site of FLK West (Diez-Martín et al., 2015).

In sum, although there was clearly an essential set of organizational concepts, or a central technological tendency, which seems to have governed how early Acheulean LCTs were manufactured and reduced, there is also a substantial amount of variability within this technological system. This variability is particularly evident when one considers early Acheulean assemblages on a site-by-site or an artefact-by-artefact basis. Here we attempt to explore the issue of how much variability existed in LCT production at a single point in time in the early Acheulean. Little is known about what behavioural and ecological mechanisms were underpinning this variability. Whether further explanation for inter-site variability relates to undocumented raw material constraints on LCT manufacture, the functional demands of capitalizing on foraging opportunities using LCTs in different landscapes, or the effects of currently undocumented variables, remain unanswered questions in early Acheulean research.

2.2. The Okote Member and early Acheulean sites therein

The temporal focus of this research is the Okote Member within the Koobi Fora Formation. The Okote Member is bracketed chronologically by the 1.56 Ma Okote Tuff and the 1.38 Ma Chari Tuff (Brown and McDougall, 2011). Around 1.5 Ma the Lorenyang lake, which formed around 1.9 Ma at the obstruction of the Omo River by the Lenderit Basalt, regressed (Bruhn et al., 2011; Feibel, 2011). While the precessional wet–dry climate cycles had only a minor effect on water input, and probably did not result in the regression of the Lorenyang lake (Joordens et al., 2011), an overall aridification trend has been documented in the region after 1.8 Ma (Bobe and Behrensmeyer, 2004; Wynn, 2004; Levin et al., 2011). The lake phase was followed by the return of a less stable Omo River system, which was characterized by a series of crevasse splay events, as well as a system of small and shallow seasonal channels in the eastern part of the basin (Rogers et al., 1994). Faunal species abundance studies and stable isotope data suggest that, within the Okote Member, the ecosystem was highly variable in space and time (Patterson et al., 2017). The volatile environmental setting of the Okote Member provides an interesting background to abundant, spatially and temporally variable archaeological sites. The Oldowan, as well as the local version of the Developed Oldowan – namely the Karari industry – in addition to the early Acheulean have all been documented within the Okote sediments (Harris and Isaac, 1997). Hominin fossils and trace fossils suggest that *Paranthropus boisei* and *H. erectus* were present at Koobi Fora between 1.56 and 1.36 Ma (Bennett et al., 2009; Wood and Leakey, 2011; Hatala et al., 2016).

The sites analysed here – FxJj65, FxJj63, FxJj37 and FxJj21 (Figs. 1 and 2) – are likely quasi-contemporaneous. The limited chronological extent of these assemblages allowed for a consideration of how artefact shape, size, and technology varied between a set of assemblages which were probably produced and used under a comparable landscape scale framework of resources (Brown and Feibel, 1985). Importantly, a single raw material (fine-grained tholeiitic basalt) was used to produce all of the studied assemblages (Braun et al., 2009b). Raw material form variability is a known driver of lithic variability in general, and is known to impact LCT morphological variability (Ashton and McNabb, 1994; White, 1995, 1998), although some authors have presented alternative perspectives (McPherron, 1994, 1999; 2000, 2003, 2006; Goren-Inbar et al., 2008; Costa, 2010; Eren et al., 2014). The limited nature of raw material variation within our dataset enables the drawing of inferences about artefact forms that are less contingent upon the properties of different stones. Differences in raw material availability – i.e. the variable distances of sites from available sources of raw material – may have influenced LCT variability at Koobi Fora. The relevant stratigraphic information, as well as the general description of the assemblages can be found in the Supplementary Online Material (SOM), sections 1 and 2 [including Figs. S1 and S2].

2.3. Documenting and interpreting LCT shape and size variability

Previous approaches to interpreting LCT size and shape variation can be classified loosely into two categories, wherein there is much overlap. First, some interpretations regard patterns in LCT size and shape variation as being representative of the ranges of final forms or end-products of hominin technological intent. Such interpretations are often adopted in studies exploring large geographic scale differences in LCT forms spanning multiple regions, where localized ecological drivers may be less relevant (Roe, 1968; Wynn and Tierson, 1990; Vaughan, 2001; Lycett and Gowlett, 2008; Petraglia and Shipton, 2008; Shipton and Petraglia, 2010). Viewing LCTs in the archaeological record in this way suggests that information about the mental templates of past LCT production is immediately accessible through observations of the forms recovered from the archaeological record (Gowlett, 1984, 2006; Wynn, 1985; McNabb et al., 2004; Pelegrin, 2009). Second, there are approaches in which LCT shape and size variation are interpreted as representing stages of, or windows onto a dynamic continuum of size and shape changes, which represent the life histories of different assemblages (Noble and Davidson, 1993; Ashton and McNabb, 1994; Jones, 1994; McPherron, 1994, 1999, 2000; White, 1995, 1998; Archer and Braun, 2010; Archer et al., 2015, 2016; Iovita et al., 2017). These approaches largely subscribe to the notion that distinguishing the influences of different variables on the forms of LCTs recovered from the archaeological record can be complex, and that the majority of LCTs likely entered the archaeological record at different stages in their life history (Jelinek, 1976, 1977; Dibble, 1995).

Both of these broader groups of approaches to interpreting LCT variability have yielded valuable insights into the behavioural patterns of Acheulean toolmakers. In this study we focus on examining variation associated with artefact life histories and then draw on alternative explanatory factors to interpret potential residual variation.

2.4. Background to methodological approach of three dimensional geometric morphometrics

The field of geometric morphometrics (GM) focusses on the statistical analysis of configurations of homologous landmarks, which approximate the structures being analysed (Slice, 2007; Baab et al., 2012). Three-dimensional geometric morphometrics (3DGM) is a sub-field of GM, and largely focusses on the analysis,

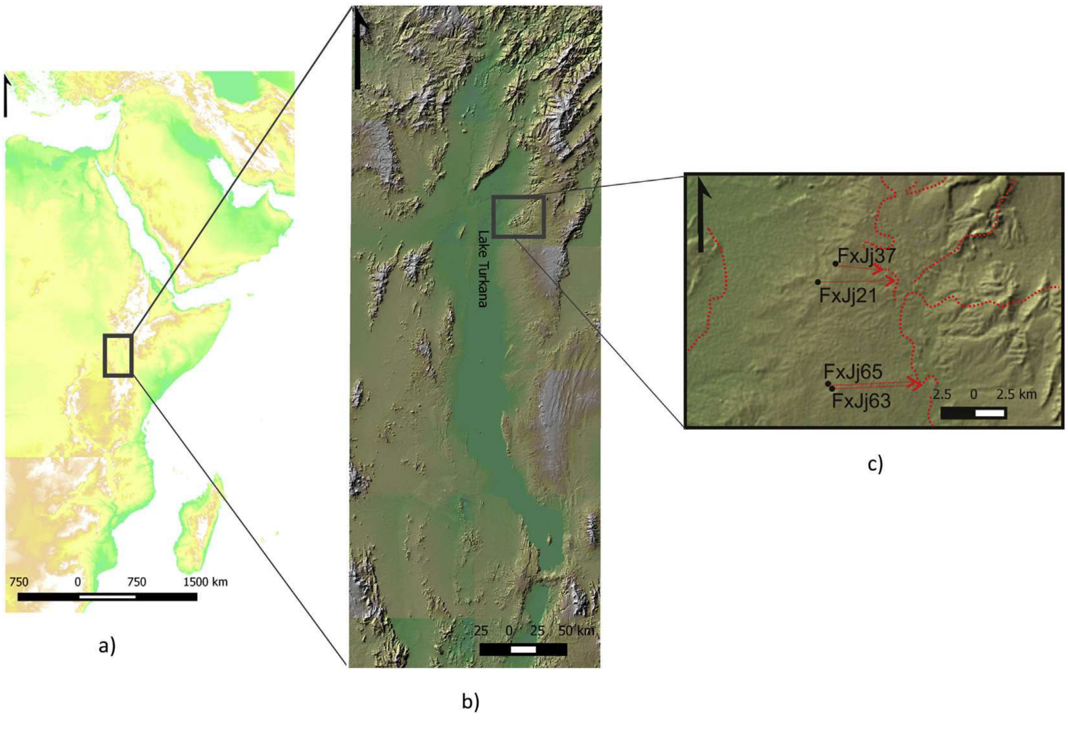

Figure 1. a) Map of eastern Africa; b) Lake Turkana; c) Image of Koobi Fora, showing the Karari Escarpment and the four sites: FxJj65, FxJj63, FxJj21 and FxJj37. The red line indicates the borders of the basalt outcrop discussed in the text and the arrows represent the minimum distance to the outcrop from each site.

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Figure 2. The excavation of the early Acheulean site of FxJj65, undertaken during the 2011 field season, showing piece plotted early Acheulean LCTs and other artefacts recovered from a single in situ artefact-bearing horizon.

visualization and relationship of three-dimensional shape and size variation with other independent variables. It was developed as a sophisticated approach to investigating biological shape variation of bones and teeth, and proceeds through the analysis of three-dimensional (3D) landmark configurations that closely approximate the overall shape of objects (Mitteroecker and Gunz, 2009; Gunz and Mitteroecker, 2013).

In comparison to fossil morphology, relatively few 3DGM studies of stone tools have been conducted, in part because of a paucity of homologous features on stone tools that creates hurdles when placing baseline anchor-point landmarks. Relatively recent developments in GM that are pertinent to stone artefact analyses use semi-landmarks (Bookstein, 1997; Mitteroecker et al., 2004). Semi-landmarks were developed to describe the interior zones of curves and surfaces of biological specimens where homologous landmarks were rare or absent (Gunz et al., 2004; Slice, 2007). Semi-landmarks are further adjusted by being 'slidden' along a tangent to the curve of a tool-edge on which they have been placed (Bookstein, 1997; Archer et al., 2017; Schlager, 2017). The sliding process aims to minimize bending energy, constituting the amount of a local shape deformation between the landmark configuration of a specimen and the mean shape of all studied specimens (Gunz and Mitteroecker, 2013). The development of semi-landmarks partly enabled the application of GM to objects, such as stone artefacts, with very few homologous landmarks (Lycett et al., 2006; Buchanan and Collard, 2007; Lycett, 2007; Lycett and Gowlett, 2008; Archer and Braun, 2010; Buchanan et al., 2012, 2015; González-José and Charlin, 2012; Lycett and Von Cramon-Taubadel, 2013; De Azevedo et al., 2014).

Early Acheulean bifaces, including the collections analysed here, often have numerous surface irregularities, and usually have one or more highly convex surfaces or faces. For this reason, we develop and apply a new GM protocol. This procedure builds on important previous studies described above, yet aims capturing the details and irregularities of variation in three-dimensional early Acheulean biface shape. Whereas many previous 3DGM biface studies focussed on automated orientation and landmarking protocols, the asymmetric characteristics of the early Acheulean specimens required them to be manually oriented, and further, that landmarks on all geometrically correspondent curves were manually digitized. Finally, a template configuration of landmarks on the two surfaces of a single LCT was deformed onto each of the other specimen meshes in the collection. This last phase of the workflow ensured geometrically correspondent co-ordinates across all edges and all surfaces of all specimens in the analysis (see Materials and methods).

3. Materials and methods

3.1. Archaeological collection

Descriptive analyses were undertaken on the entire collections of LCTs from FxJj65, FxJj63, FxJj37, and FxJj21 which are located at the National Museum of Kenya (n = 270, Table 2) (Figs. 3 and 4). 3DGM analyses were only undertaken on complete, unbroken specimens with clearly defined tips and bases (n = 214). In other words, specimens that had fractures that modified their original sizes and morphologies were excluded from the 3DGM analysis. In addition, LCTs which did not have clearly definable elongation axes (technological length and width) – thus making them difficult to orient accurately – were not included in the 3DGM analysis. There is an unavoidable unequal distribution of numbers of specimens between sites (Table 2). Nevertheless, this imbalance does not violate any assumptions regarding general linear model stability (Quinn and Keough, 2002).

Table 2
The breakdown of the artifacts from four archaeological sites analyzed in the study.

	FxJj65	FxJj63	FxJj37	FxJj21	Total
LCTs	118	97	38	17	270
Cores	29	34	28	7	98
Débitage products	678	1964	664	110	3416
Total:	825	2095	730	134	

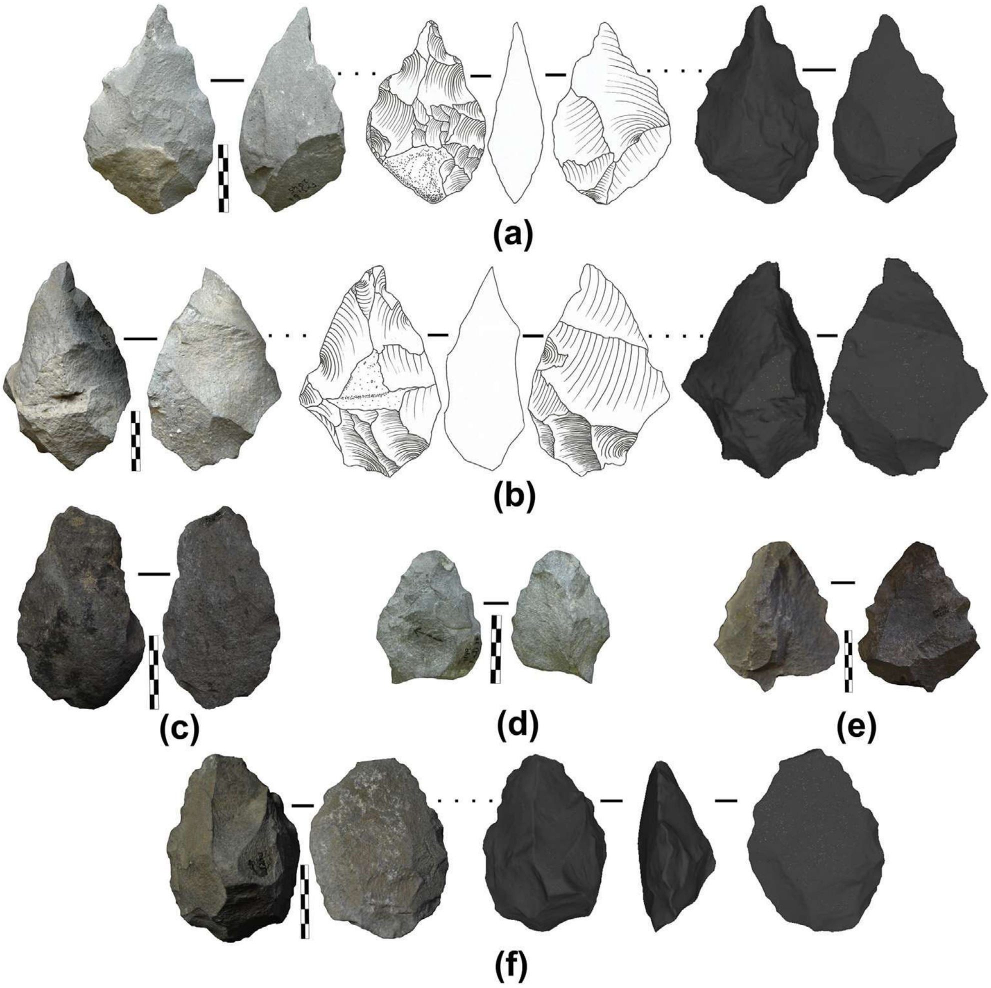

Figure 3. Archaeological LCTs from the four sites: (a) FxJj63_2045 (photograph, drawing, 3D scan); (b) FxJj63_1375 (photograph, drawing, 3D scan); (c) FxJj65_134 (photograph); (d) FxJj37_1149 (photograph); (e) FxJj65_701 (photograph); (f) FxJj63_1200 (photograph, 3D scan). Scale bar = 5 cm.

3.2. Experimental collection

To facilitate our interpretation of patterns of artefact reduction stages in the archaeological data and to interpolate stages that might be missing, an experimental collection of LCTs was generated (SOM Fig. S3). The experimental LCTs were produced within the published parameters of early Acheulean technological strategies (de la Torre and Mora, 2005; de la Torre, 2011; Beyene et al., 2013). For example, no repetitive bifacial alternations between knapping surfaces were undertaken, which is a typical characteristic of classic Acheulean bifaces, yet is far less common in early Acheulean assemblages (de la Torre et al., 2008). In all experimental reduction sequences, the majority of removals were non-invasive, and focused on a single knapping surface that in most cases constituted the dorsal surface of the original flake blank.

One of us (WA) carried out the experimental LCT production. The knapper who produced the experimental collection did not participate in the analysis of the archaeological collections, yet was guided by the knowledge from the literature of the strategies which are conventionally associated with early Acheulean LCT manufacture (non-invasive removals, no repetitive alternations between surfaces). We used large flake blanks of fine-grained volcanic rock (basalt and phonolite), which broadly resembled the limited spectrum of raw material variation in the archaeological dataset. Large and small blanks were selected for experimentation based upon our current knowledge of the blank variation in LCTs in the archaeological collections (SOM Fig. S4).

We divided each experimental LCT production trajectory into four categories. These typological categories or phases are descriptive and have little or nothing to do with LCT morphology. The reduction stages at which we collected these data were determined solely by the number of flakes removed in any given experiment (Table S4). We scanned and generated landmark configurations, and other data (Table S4) that reflect the technological signature at each of these stages. This resulted in an experimental dataset of 18 specimens.

3.3. Description of LCT production sequences

Chaîne opératoire analysis treats stone tool production as an all-encompassing dynamic behavioural system, which starts with raw material procurement and proceeds through the consideration of various manufacture, maintenance and discard phases (Sellet, 1993). Here we focus on the chaîne opératoire of early Acheulean LCTs. In addition, we provide attribute data on LCTs including size, scar count, cortex percentage and blank type (de la Torre, 2011). We also classify LCTs into different categories based on scar removal patterns. In the SOM we present a brief

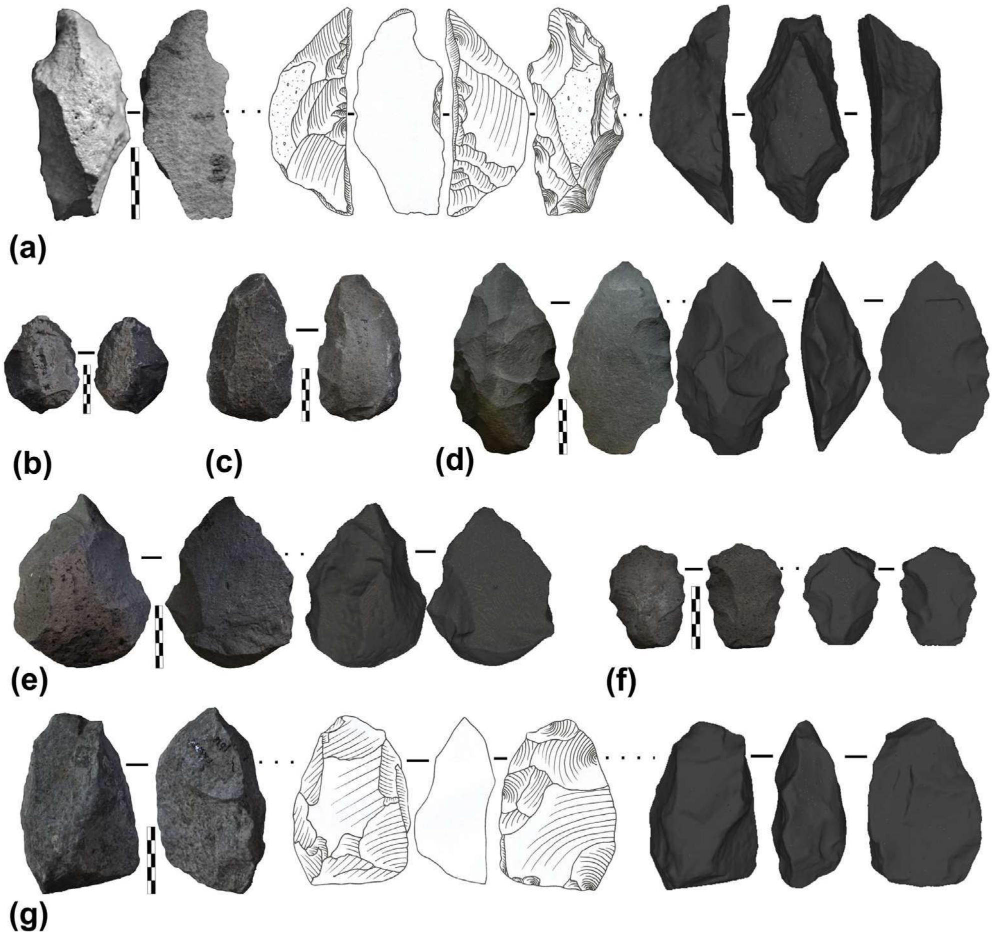

Figure 4. Archaeological LCTs from the four sites: (a) FxJj63_1713 (photograph, drawing, 3D scan); (b) FxJj21_11 (photograph); (c) FxJj21_14 (photograph); (d) FxJj63_D (photograph, 3D scan); (e) FxJj65_334 (photograph, 3D scan); (f) FxJj21_68 (photograph, 3D scan); (g) FxJj37_1678 (photograph, drawing, 3D scan). Scale bar = 5 cm.

description of the débitage products and the Mode 1 cores associated with these LCT assemblages.

3.4. Scanning and 3D geometric morphometrics

All LCTs were scanned with a Next Engine surface scanner, and meshes were subsequently cleaned, trimmed and fused using a combination of Next Engine ScanStudio and Mesh Lab software (v. 1.3.4.BETA). The overall asymmetry and multi-facial characteristics of a number of the LCTs prevented us from using an automated approach to placing appropriate landmarks (e.g. Archer et al., 2015). Rather, initial landmarks were manually placed on the LCT tips, bases and the lateral edges using the Landmark v3 software (Fig. 5). The 3D coordinates of the tip and the base constituted the only geometrically correspondent individual landmarks at the outset, on each LCT. As the accuracy of subsequent semi-landmark placement relied on the initial placement of these two points (tip and base), only specimens with clearly defined tips and bases were selected for the 3DGM component of this study (n = 214 [FxJj65 = 97, FxJj63 = 75, FxJj37 = 28, FxJj21 = 14]).

The LCT meshes were initially oriented in two orthogonal planes, namely, 1) the axis linking the tip and base (the technological length axis), and 2) the plane orthogonal to 1). The second orientation plane 2) was therefore perpendicular to, and intersected the two biface faces. In addition, the second orientation step 2) ensured that the most convex surface of each biface always faced the same direction. Forty semi-landmarks were then manually placed on each of the two edges of each LCT. The landmarks on each edge were then equidistantly spaced in three-dimensions using the “digit.curve” function in the Geomorph package in R (Adams and Otárola-Castillo, 2013).

Three hundred and twenty landmarks (160 on each LCT face) were then placed on the two surfaces of a randomly chosen single template LCT specimen. This template configuration of landmarks was then digitally deformed onto the surfaces of each of the other LCT meshes in the collection using functions in the Morpho R package (Schlager, 2017). This deformation was undertaken to obtain geometrically correspondent surface coordinates on all LCT specimens in the analysed assemblages (Fig. 6). This process resulted in a configuration of 362 geometrically correspondent landmarks for each specimen. All LCT landmark configurations were then adjusted using Procrustes superimposition, which standardizes size, orientation, and position amongst specimens (Rohlf and Slice, 1990).

3.5. Description of independent LCT measurements

To investigate the effects of behaviours associated with tool reduction on LCT allometry, we formulated a set of variables (size, scar count, edge angle coefficient of variation [CV], cortex coverage, and knapping platforms) which we hypothesized would track LCT reduction in the LCT assemblages. We first investigated how these independent variables interacted with LCT shape and size in the experimental collection. This provided a control sample, in which

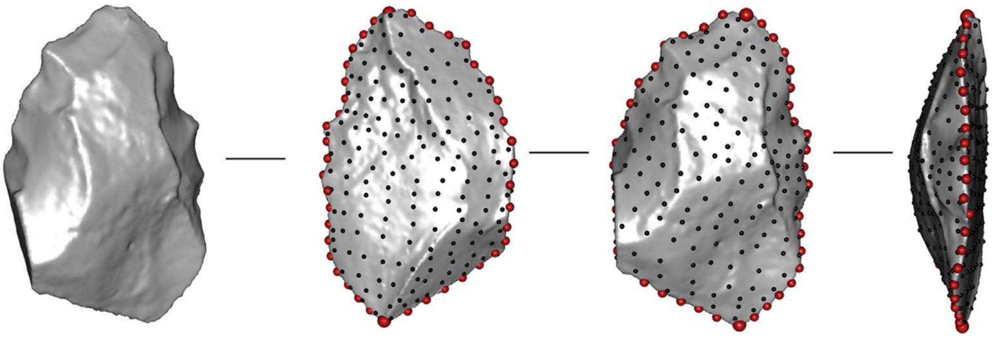

Figure 5. The LCT template used in the deformation (see Methods), with manually placed semi-landmarks on the two edges (the red landmarks on the tip and the base are enlarged), and on both surfaces (black landmarks). All edge-landmarks were resampled using the geomorph package in R (Adams and Otárola-Castillo, 2013).

the different stages of reduction represented by different LCTs were present. Based on our understanding of patterns of size and shape variation in the experimental data, we then drew inferences regarding the factors underpinning specific aspects of LCT variation in the archaeological data. This inferential link will be discussed further below (section 3.5).

Size Centroid size was calculated as the square root of the sum of squared distances from the landmarks in a configuration approximating a specific artefact's shape, to that configuration's centroid (McPherron, 1995, 1999; Shott and Weedman, 2007; Baab et al., 2012). In this study, centroid size of archaeological data correlated with the linear measurements of length ($r = 0.93$), mass ($r = 0.91$), width ($r = 0.79$) and thickness ($r = 0.66$). We used both mass and centroid size as proxies for overall LCT size in the analyses.

Scar count Scar count refers to the number of visible flake removals on a given artefact. In several studies, the number of removals has been used as a proxy for reduction intensity (Clarkson, 2013; Shipton and Clarkson, 2015). This variable is partially dependent on overall artefact size. We therefore used the ratio of scar count to two-dimensional LCT area, to account for size related effects (Braun et al., 2008b).

Edge angle CV It has been demonstrated for various bifacial tool collections, ranging from the Acheulean to the Holocene, that the edge angle on a bifacial tool is a good proxy for the extent of reduction of that tool (Goodyear, 1974; Hoffman, 1985; Boëda and Richter, 1995; Iovita, 2014; Archer et al., 2016). Here edge angles were computed along the two edges of the oriented artefact meshes with an automated measurement protocol (see the SOM, section 4). Edge angles were measured at the positions of each landmark along each of the edges of each LCT (Fig. 6). This resulted in 40 edge angle measurements for each LCT.

It was important to reduce, or synthesize the number of angles per specimen into a single measurement. For instance, Archer et al. (2016) used median edge angle, and Iovita (2014) used mean edge angle as indicators of reduction intensity in bifacially flaked artefacts. We hypothesized that neither mean or median would be representative of these 40 measurements due to the bifacially asymmetric nature of early Acheulean LCT morphology. We know from early Acheulean literature that LCTs generally have relatively inconsistent and variable edge angles (Kuman and Gibbon, 2017). More specifically, partially reduced LCTs have more removals closer to the tip of the LCT. In these instances, the edge angles at the tip of the LCT are relatively smaller than the angles at base, which often remains unworked. The result of this reduction pattern is that the edge angles of marginally reduced specimens are extremely variable. We hypothesized that as reduction progresses the edge angles around the LCT tip and base should become more homogeneous. To quantify these changes in the homogeneity of angles within an artefact we chose to use the coefficient of variation for angle measurements within a single specimen. More extensively reduced

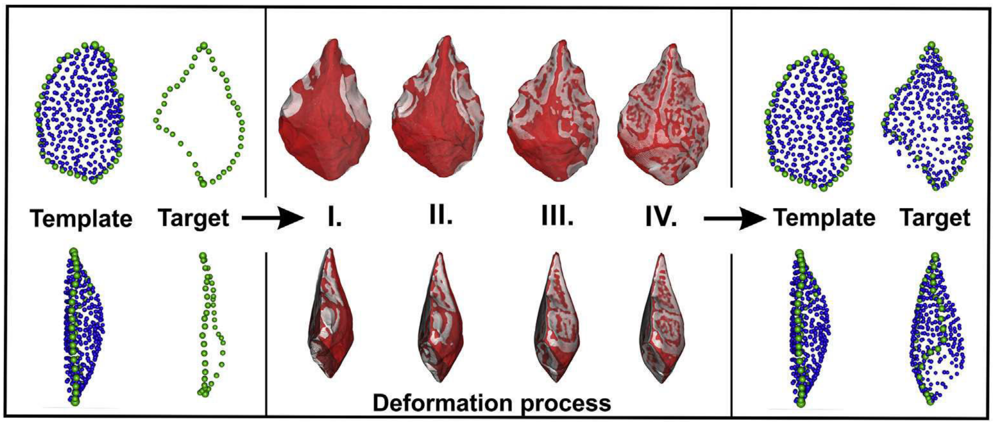

Figure 6. Illustration of the deformation associated with the projection of the surface landmarks from the template onto a target specimen. In each iteration (I–IV), the template mesh (red) is gradually warped onto the target mesh (grey), ultimately estimating the position of each surface landmark on the target mesh. The green points are edge semi-landmarks whereas the blue points are the surface semi-landmarks.

LCTs should have lower coefficients of variation than less reduced specimens.

Cortex coverage The relative coverage of 'cortex' (i.e. the natural surface crust of a nodule of stone) has been demonstrated to be a reliable proxy for the degree of reduction in a number of different artefact typological categories (Toth, 1982; Sullivan and Rozen, 1985; Dibble et al., 1995; Braun et al., 2008b). Following the protocol of Roth and Dibble (1998), we visually estimated the percentage of the surface covered by cortex using the classifications of 0%, 1–10%, 11–40%, 41–60%, 61–90%, 91–99% and 100%.

Knapping platforms 'Knapping platforms' refers to the number of striking surfaces from which flakes were struck on an LCT. This variable potentially tracks both the intensity of tool reduction, as well as the strategic decisions made by knappers with regard to how frequently cores were rotated during tool reduction (Delagnes and Roche, 2005; Douglass et al., 2017). We used the number of knapping platforms documented on each artefact as a covariate in our analyses.

3.6. Statistical analyses

We used multivariate statistics to evaluate the differences between LCT shapes from the four sites. The major axes of shape variation in the archaeological LCT assemblages were visualized with principal components analysis (PCA), and a bivariate plot of principal component (PC) 1 and 2 scores. Further, maximum and minimum theoretical LCT shape extremes were calculated and visualized for the major axes of shape variation, and each of the sites was plotted as different coloured points on the bivariate plot.

Differences in mean LCT shape between the archaeological sites were investigated using multivariate analysis of variance (MANOVA, Type II) on the first 12 principal components of LCT shape variation. This analysis was undertaken to test whether there were statistically significant differences between the mean LCT shapes from the four archaeological sites. For this purpose, we used the function "Manova" in the R package "car" (Fox and Weisberg, 2011).

The effects of the independent variables (described in section 3.5 above) on LCT shape were examined using multiple regression, primarily to document which components of LCT shape were driven by patterns of LCT manufacture and maintenance. As the experimental LCTs were associated with known stages of reduction, we used the experimental data to explore both a) the general changes in size and shape associated with LCT reduction, as well as b) the combination of independent variables which best explain these changes. In this vein, a combination of independent predictors was defined to estimate the extent of LCT reduction in the experimental dataset. In this experimental model the degree of LCT reduction (as approximated by number of removals) (Shipton and Clarkson, 2015) comprised the response variable while edge angle (CV), size (mass), cortex and knapping platforms comprised the predictors.

We established that the predictors of size and edge angle (CV) independently explained variation in LCT reduction within these experimental assemblages extremely well (see Results section 4.2). The results of the linear model on the experimental dataset enabled us then to fit the same model to the archaeological shape data, to assess which component of archaeological shape variation this combination of predictors explained.

All procedures associated with multiple regression model fitting and testing of assumptions were performed in R version 3.4.1 (R Core Team, 2017). To check the validity and stability of the models, various diagnostics tests were undertaken including Cook's distance, DFBetas, DFFits, leverage and Variance Inflation Factors, and the distribution of residuals and residuals plotted against fitted values. No models discussed in this paper deviated substantially in terms of these assumptions. To test the significance of the effects of each of the independent variables, we compared the fit of the full model (the model including all the predictors of interest) with that of the null model, comprising only the intercept (Forstmeier and Schielzeth, 2011). To homogenize the values of predictors which had substantially different scales (such as edge angle and reduction stage for example), all predictors were standardized with a z-transformation which makes the predictor's mean value equal to 0 and standard deviation equal to 1 (Aiken and West, 1991).

Finally, to investigate aspects of LCT shape related to variables other than reduction, we adjusted the LCT landmark configurations to minimize the effects of reduction on LCT shape, following the protocol described by Archer et al. (2016). In short, we fitted a linear model regressing the Procrustes shape coordinates of the archaeological LCTs on both centroid size and edge angle (CV). The residuals of this model were then treated as the aspects of shape variation remaining once the effects of tool reduction were minimized.

4. Results and preliminary discussion

4.1. Description of LCT production sequences

Blank type selection and evidence for on-site tool production Large flakes served as blanks for the majority of LCTs from all four sites (Fig. 7). The assemblages from FxJj21 and FxJj37 represent an anomaly in that many of the LCTs are heavily reduced. In many of these specimens it is therefore not possible to document the original blank morphology. In a small number of cases at FxJj65 and FxJj63, cobbles or angular blocks were used as LCT blanks (Fig. 7). SOM Figure S7 illustrates the range of blank sizes used by knappers in the production of LCTs at all four sites by plotting the fourth size quartile of flakes (i.e. the larger flakes in the assemblages that are more likely to have been associated with LCT production than the more diminutive flake sizes).

No evidence for on-site large flake production (e.g. boulder cores) has thus far been documented at the site of FxJj65. Unmodified large flakes, however, are abundant in the collection but – due to the lack of boulder cores – were likely manufactured off-site, but perhaps in close proximity to the FxJj65 locality. 'Off-site' large flake production patterns have been previously described for other early Acheulean localities such as Peninj, Melka Kunture, West Turkana (de la Torre et al., 2008; Harmand, 2009; Gallotti, 2013), and therefore may be a more common feature of landscape-scale patterns of early Acheulean LCT production.

The site of FxJj37 presents another case of off-site blank production. The reduced size of the FxJj37 LCTs relative to the other sites analysed, and the absence of large unmodified flakes or cores from which large flakes could be struck suggests that flake blanks were not produced on-site. A number of small cores were present in the FxJj37 collection, yet none of these cores are likely to have been utilized for blank production associated with LCT manufacture. SOM Figure S8 shows that the sizes of LCTs produced on flakes from FxJj37 are bigger than the unworked flakes found at FxJj37. This suggests that none of the flakes present at FxJj37 were intended for LCT manufacture, and that the blanks associated with LCT production at FxJj37 were likely produced elsewhere on the landscape.

Large flake blanks for LCT manufacture were produced onsite at the locality of FxJj63. A single large boulder core (6 kg) was recovered at the site (Fig. 8), which had three large flake negative removals that were 10–20 cm in maximum diameter. The boulder core had a non-cortical knapping platform which was prepared with two to three removals, and from that platform, two to three big flakes were detached (Fig. 8). Importantly we identified a refit

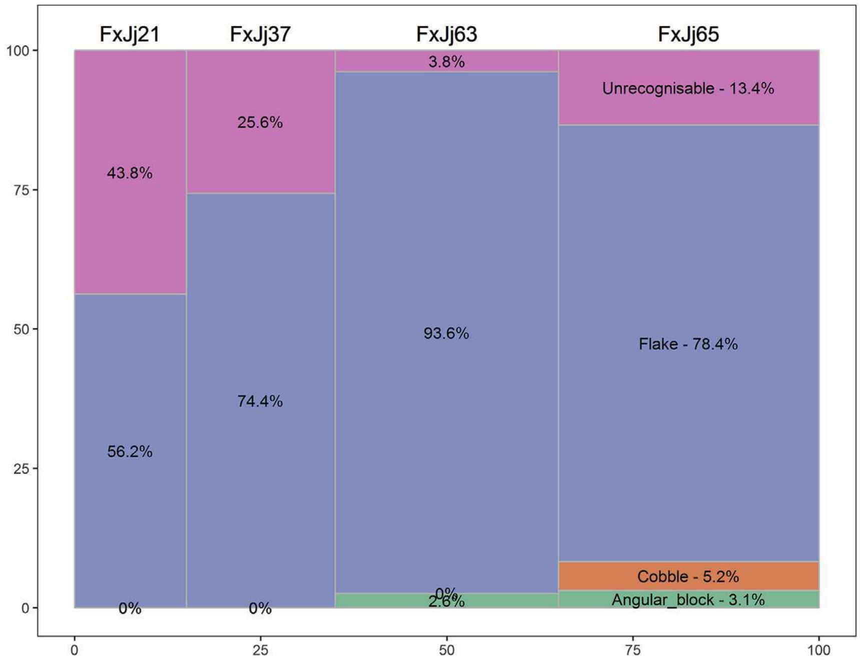

Figure 7. The percentages of blank types used for LCT manufacture at the four sites. For this mosaic plot, each bar width is scaled in accordance with relative sample size. Each axis represents 0–100%.

between a large flake blank and a core in the collection (Fig. 8). This particular refitted blank is an example of the Kombewa method, commonly used for blank production in Acheulean LCT production contexts (Texier and Roche, 1995; Inizan et al., 1999; Sharon, 2009). The negative removals evident on the cores, as well as the blanks in the collection were predominantly side-struck flakes, that is, flakes with platforms perpendicular to their maximum length axes. In addition, side-struck flakes were recognizable on marginally shaped LCTs which retained remnants of the platforms of the blanks on which they were manufactured. Siret blanks (flakes split during their production along their length axes) are examples of unusual blank forms used for LCT production at FxJj63. In contrast to FxJj63, there is little evidence available within the small collection from FxJj21 to reconstruct LCT blank production patterns.

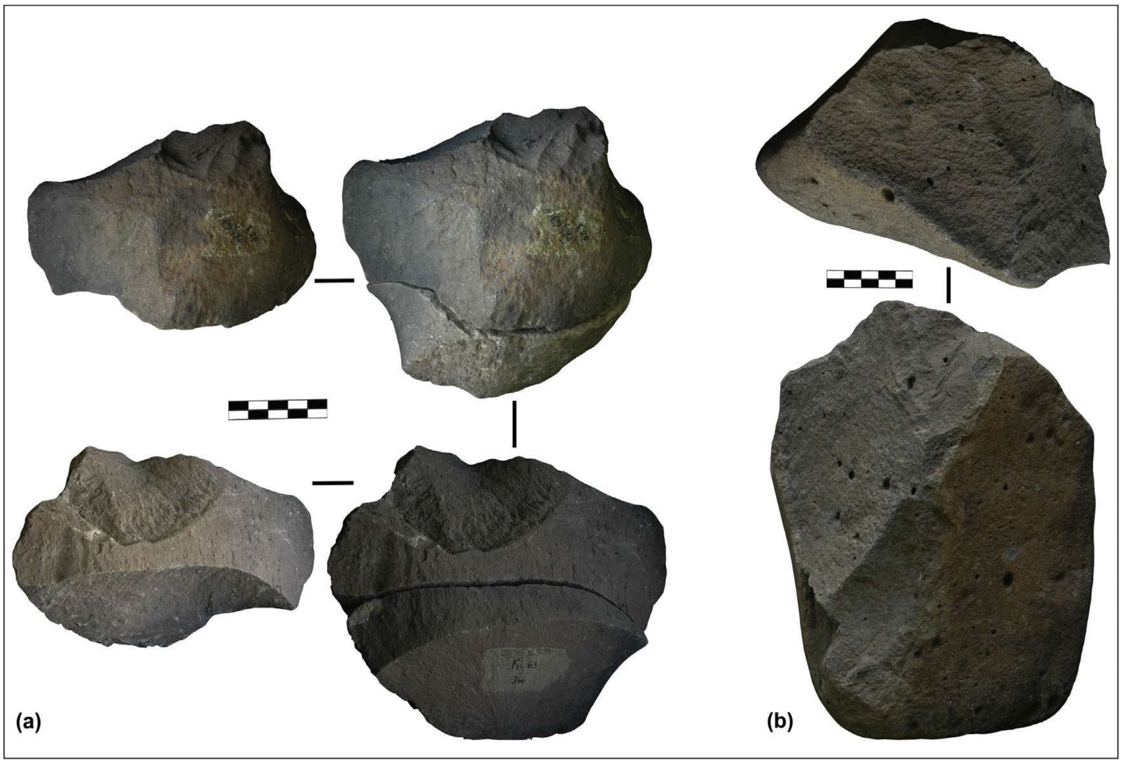

Figure 8. Two examples of large-boulder cores from FxJj65. The images on the left represent a core and a refit between this core and a large flake. Scale = 5 cm.

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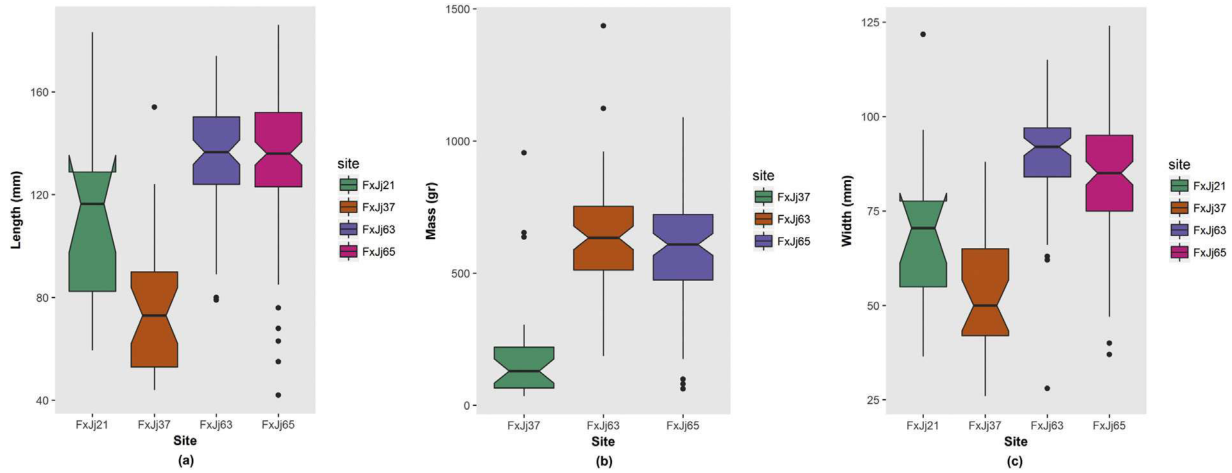

Figure 9. The metric parameters of LCTs including Length-mm (a), Width-mm (b) and Mass-gr (c). The line of the notched box plot shows the median, while the notch represents the 95% Confidence Interval. The plot was made using the ggplot2 R package (Wickham, 2009).

LCT parameters The LCTs from the four sites exhibit statistically significant differences in metric parameters of mass (one-way ANOVA, $p < 0.001$ degrees of freedom [df] = 2), length (one-way ANOVA, $p < 0.001$ df = 3), width (one-way ANOVA $p < 0.001$ df = 3), and scar count (one-way ANOVA, $p < 0.001$ df = 3) (Figs. 9 and 10) (see SOM Table S7 for more details). Large cutting tools at FxJj65 and FxJj63 appear to be longer, wider and heavier compared with LCTs from the FxJj37 and FxJj21 sites (Fig. 9). The sites of FxJj21 and FxJj37 also exhibit more removals indicating they were more intensively reduced (Fig. 10). Large cutting tools from FxJj37 and FxJj21 are largely non-cortical, falling in either the 1–10% category or the 0% category (Fig. 11). In contrast, both FxJj65 and FxJj63 have highly variable distributions of cortex (Fig. 11).

LCT production Several different LCT production patterns were observed at the four sites. Bifacial reduction of LCTs focused on the reduction of two removal surfaces. Namely, a single preferential removal surface and a subsidiary removal surface which had the purpose of serving to facilitate the intended removals from the preferential removal surface. An extension of this bifacial reduction strategy is where the removals on the preferential surface were made in a centripetal manner (Fig. 12). Another variant of the bifacial strategy could be referred to as a ‘discoidal bifacial strategy’, which results in a small LCT with centripetal removals on both surfaces. This discoidal bifacial strategy constituted a manufacture process where the single preferential surface was not clearly defined, since equal numbers of similar removals were struck from both surfaces. Repetitive alternation between two knapping surfaces – which is a typical characteristic of later Acheulean biface production – was only observed at the site of FxJj21.

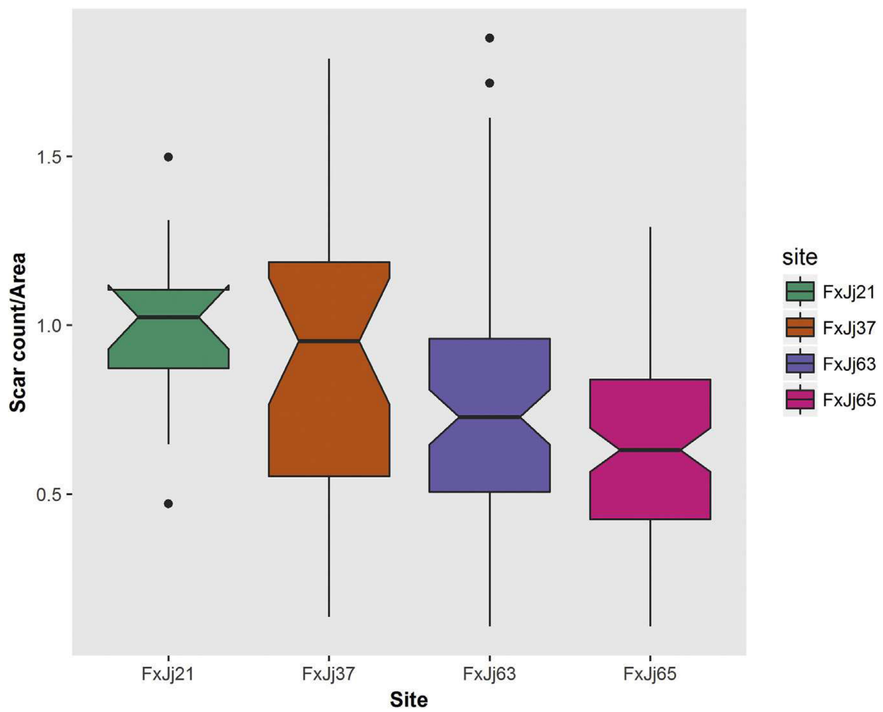

Figure 10. Scar counts divided by area. The line of the notched box plot shows the median, while the notch represents the 95% confidence interval. The plot was made using the ggplot2 R package (Wickham, 2009).

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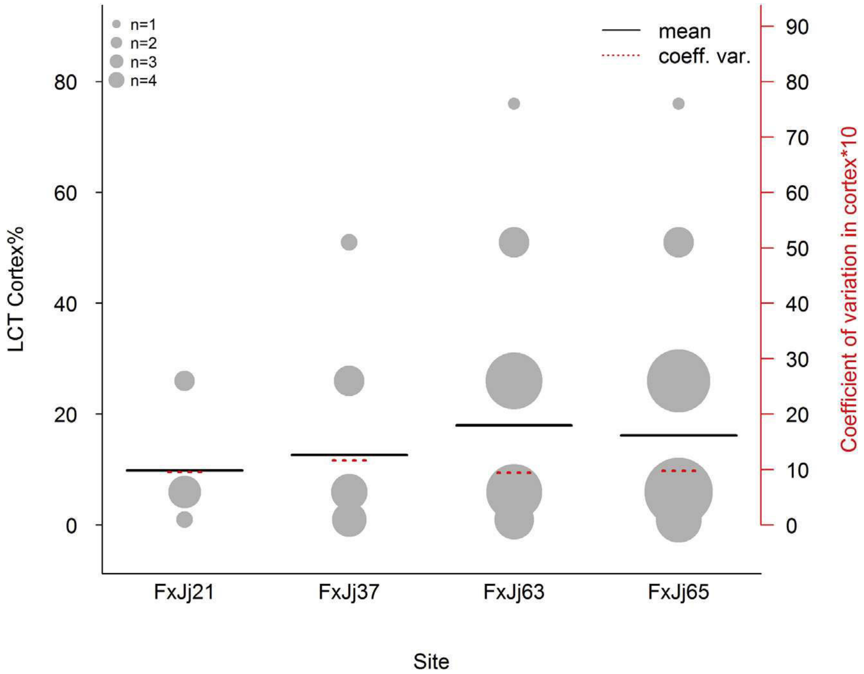

Figure 11. The percentage of cortex on LCTs, as well as the scaled cortex coefficient of variation (coeff. var.) for each of the sites. The size of the bubble corresponds to sample size i.e. the legend on the top left provides a key to how the size of the bubbles should be interpreted with regard to the number of LCTs associated with a particular percentage of cortex.

Unifacial reduction was another variant in LCT production. The unifacial strategy focused removals on one removal surface of the LCT. In 82% of specimens produced by this strategy, the ventral surface of the original flake blank constituted the striking platform for removals. The purpose of these removals was to shape the dorsal surface of the original blank, which is a similar strategy to what has been reported at other early Acheulean sites such as Peninj, Lake Natron and EF-HR at Olduvai Gorge (de la Torre and Mora, 2005; de la Torre et al., 2008). In only 9% of the cases was the purpose of this strategy to shape the ventral surface of the blank. In the remainder of LCTs produced with unifacial reduction (9%), the blank was not a flake and thus the dorsal/ventral dichotomy is not relevant. Some unifacial specimens exhibit removals made in a centripetal manner, suggesting that the differences between bifacial and unifacial reduction strategies were subtle. Within the bifacial and unifacial reduction strategies, invasive removals, which encroach on over 50% of the removal surface, are infrequent relative to the more abundant shorter, non-invasive removals.

One rare strategy, which we refer to as 'dorsal ridge reduction', was used to produce four LCTs, two bifacial and two unifacial. Here, shaping removals are located in a place on the LCT that is not worked in the application of any of the above mentioned strategies.

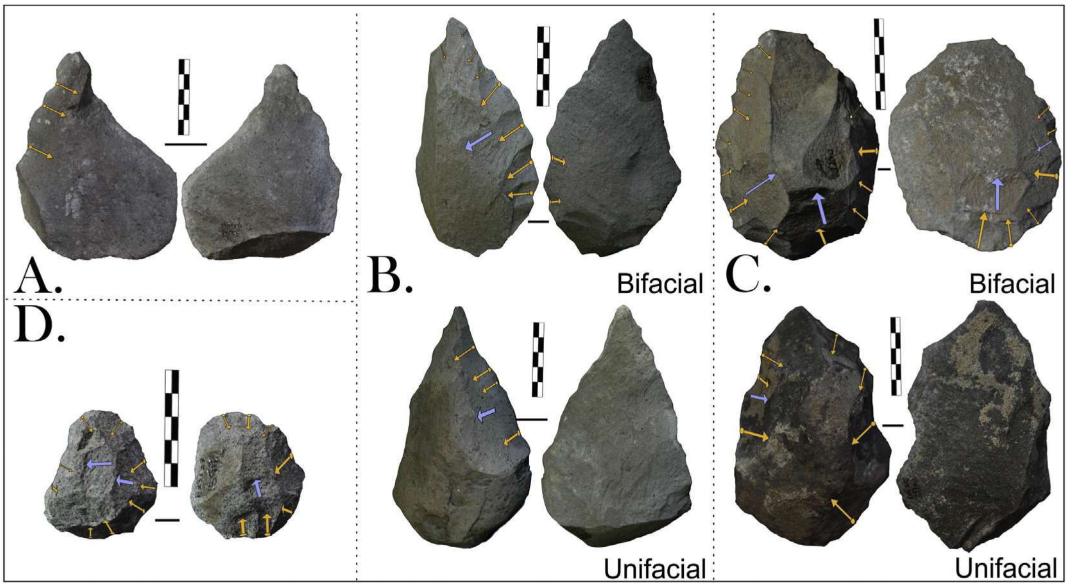

Figure 12. The four LCT reduction techniques discussed in the text: A: non-invasive marginal pieces, B: unifacial or bifacial pieces with non-centripetal removals, C: bifacial or unifacial pieces with extensive centripetal removals on one or both surfaces, D: extensively reduced bifacial pieces. Yellow arrows indicate primary removals and blue arrows indicate secondary removals. Scale = 5 cm.

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In this strategy, the additional removals are located on the dorsal surface of the original flake. The volumetric ridge that runs through the mid-section of the dorsal surface served as the knapping platform for removals.

The last strategy we describe as 'non-invasive marginal'. This was applied to produce LCTs which had only one to three entirely non-invasive removals, modifying the original blank only marginally. These non-invasive removals were initiated along the edges of either the ventral or the dorsal surfaces of the flake blanks. In this vein, in specimens where this strategy was applied, the morphology of the initial blanks closely resembled the final LCT form, which is why the shaping removals were always minimal in number and were minimally invasive. The differences between the four described techniques are subtle. One possibility is that these techniques grade into one another, and that this gradation may be underpinned by reduction extent.

One could imagine a reduction scenario where non-invasive marginal LCTs represent the earliest reduction stages. In this scenario, non-centripetal unifacial or bifacial pieces may be more extensively reduced, and fully centripetal scar patterns may be representative of yet further reduced specimens. Fully discoidal, ovate looking specimens are likely even further reduced and may represent resharpened specimens. In this scenario, the techno-typological categories may in fact be representative of differential stages of a single reduction continuum. Figure 12 shows examples of the reduction strategies described here, and Figure 13 provides the breakdown of the proportions of each strategy within each site.

Artefact size and density Figure 14 plots artefact size and frequency distributions of artefacts from each site. The site FxJj37 has significantly different artefact density distributions and counts than the sites of FxJj63 and FxJj65. FxJj37 site has relatively small numbers of finds and normal distributions of artefact sizes. However the sites of FxJj63 and FxJj65 have much higher numbers of finds and have multimodal artefact size distributions (with two peaks). This multimodality at FxJj63 and FxJj65 is what one would expect at sites where hominins were provisioning, in other words, producing small flakes as by-products of different phases of manufacture, and large products associated with LCT blank production (Binford, 1979).

4.2. Geometric morphometrics

Experimental LCT reduction None of the diagnostic tests indicated obvious influential cases that could unduly affect the regression slope, or significant deviations from the assumptions of normality and homogeneity of residuals (Quinn and Keough, 2002; Field, 2005). A likelihood test comparing the full and null models (the model excluding the predictors of interest) suggested that the combined influences of edge angle (CV), mass, knapping platforms and cortex on number of removals, are highly significant ($F = 16.84$, $p = 0.003$, $df = 8$). The r^2 of the model is exceptionally high (0.91). Both edge angle (CV) and mass were highly significant predictors of LCT reduction in the experimental collection (see Table 3).

Edge angle (CV) had a negative estimate as a predictor of reduction (i.e. as a predictor of number of removals) (Fig. 15). This means that as the process of LCT manufacture progressed, edge angle (CV) simultaneously decreased. This indicates that LCT edges become more regular during the process of LCT manufacture. This finding is convincing from a pragmatic knapping perspective, as a primary objective in 'roughing out' bifacial blanks is to remove surface irregularities until the edges of the ébauche approach bifacial symmetry (Inizan et al., 1999:146–147; Archer and Braun, 2010).

Surprisingly, neither a) cortex coverage nor b) number of knapping platforms were significant predictors of extent of experimental LCT reduction. Therefore, these last two variables were not included in the model focused on developing predictions for the archaeological data.

LCT shape variability between the four localities Principal component 1 explains 20% of the variance and PC2 explains 14% of the variance (see SOM section 6, Table S8, Figs. S9 and S10). Further, MANOVA conducted on the first 12 PCs using site affiliation as the sole predictor shows that although there is clearly substantial

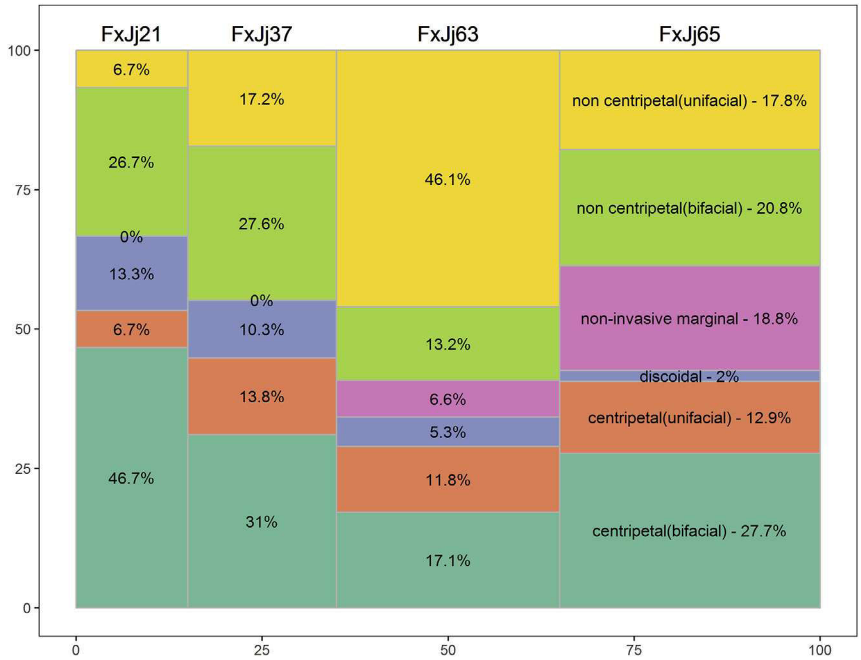

Figure 13. The percentages of descriptive reduction stages represented in the four sites. Each bar width is scaled in accordance with relative sample size. Each axis represents 0–100%.

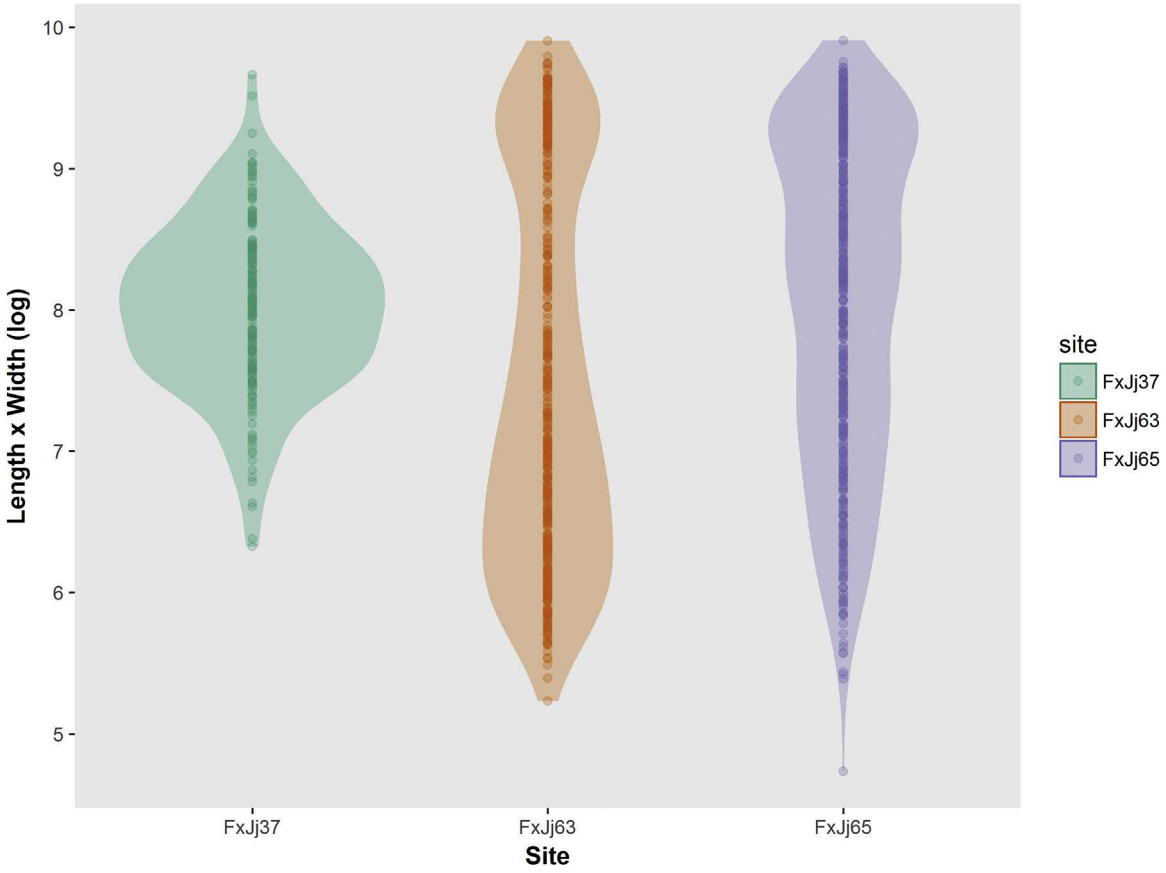

Figure 14. Violin plots showing artefact size (cm) and density distributions by site. Note the multimodal distributions of the FxJj63 and FxJj65 sites. The plot was made using the ggplot2 R package (Wickham, 2009).

overlap on PCs 1 and 2, statistically significant differences exist in LCT shapes between the four sites ($F = 2.669$, $p < 0.001$ $df = 3$). These results suggest that the structure of LCT variance within each of the sites is largely the same, but that the mean shape of LCTs is significantly different. Despite these statistical differences between the collections of LCTs from each of the sites, it is clear from the PCA that there is also substantial overlap in the ranges of variation between the sites. Theoretical shapes calculated for the maximum and minimum of PC1 (Fig. 16) reveal a change from an elongated minimum PC1 to an ovate maximum PC1. On PC2, theoretical shapes show morphological changes specifically in the tip and the base zones of the LCTs.

Table 3
Shows the estimates and associated t and p-values for the model on the experimental data. The linear model is the following: number of removals ~ edge angle (CV) + mass + knapping platforms + cortex + experimental group. Edge angle (CV), mass, knapping platforms and cortex are test predictors, while experimental group here is a control predictor.

Effect[b]	Estimate	SE	t	P	Lower CI	Upper CI
Intercept	15.275	5.013	[a]	[a]	2.388	28.163
Edge angle (CV)	−28.215	9.170	−3.077	0.028	−51.787	−4.643
Exp. Group 2	11.599	2.252	5.151	0.004	5.811	17.388
Exp. Group 3	8.313	1.837	4.526	0.006	3.591	13.034
Exp. Group 4	7.302	4.198	1.739	0.142	−3.491	18.094
Exp. Group 5	2.961	1.980	1.495	0.195	−2.130	8.051
Mass	−0.040	0.010	−3.899	0.011	−0.066	−0.014
Knapping pl	0.907	0.534	1.697	0.151	−0.467	2.280
Cortex	3.036	1.575	1.927	0.112	−1.013	7.085

[a] Not shown because of not having a meaningful interpretation.
[b] Covariates edge angle (CV) and mass were Z transformed to a mean = 0, and sd = 1.

Assessing the effects of reduction on archaeological LCT shape Comparison between the full and null model indicated that the effects of edge angle (CV), centroid size and site on archaeological LCT shape are highly significant ($F = 10.54$, $p < 0.001$, $df = 5$) (Table 4 and Fig. S12). Bivariate plots of PC1 versus these covariates illustrates that a similar overall pattern is clearly visible in centroid size for all of the sites (Fig. 16). However, the relationship between edge angle variance and PC1 appears to be different for FxJj21 than for the other three sites (Fig. 16).

This multiple regression model assessing the effects of reduction on archaeological LCT shape suggests that the major axis of archaeological LCT shape variation is underpinned by the influence of hominin behaviours associated with LCT reduction, and that the differences in LCT shapes between the sites investigated here may be associated with tool manufacture and maintenance behaviours. The LCTs appear to vary from an elongated and large, less reduced morphology, to a more discoidal and intensively reduced form. Interestingly some specimens exist with both high PC1 values and large centroid sizes. These LCTs are mostly unifacial, have only marginally reduced edges, and closely resemble the oval shapes of their original flake blanks. This trajectory of shape change on PC1 therefore documents the presence of three recognizable stages of reduction. Although not discrete, these stages are a) marginally reduced LCTs, with oval shapes which closely resemble original blank forms, b) elongated, extensively reduced specimens and c) discoidally shaped, exhaustively reduced specimens where the biface tips have been longitudinally maintained or resharpened.

We subsequently investigated whether this trajectory of shape change associated with reduction differed between archaeological sites, when viewed independently (Fig. 16). The patterns of shape

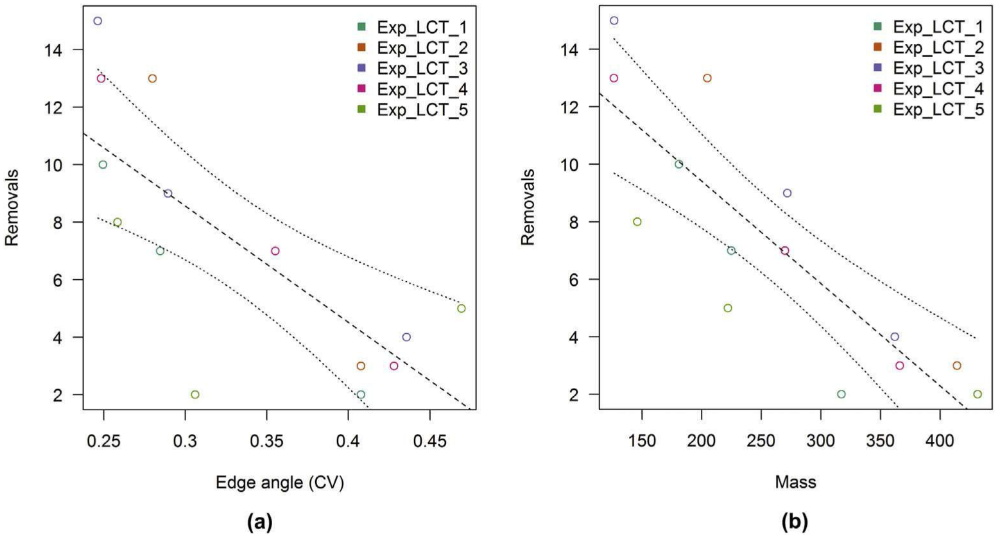

Figure 15. Number of removals as a response to (a) Edge angle (CV) in degrees and (b) Mass in g, for different experimental (Exp_LCT) sequences (1–5). The dotted lines indicate 95% confidence intervals.

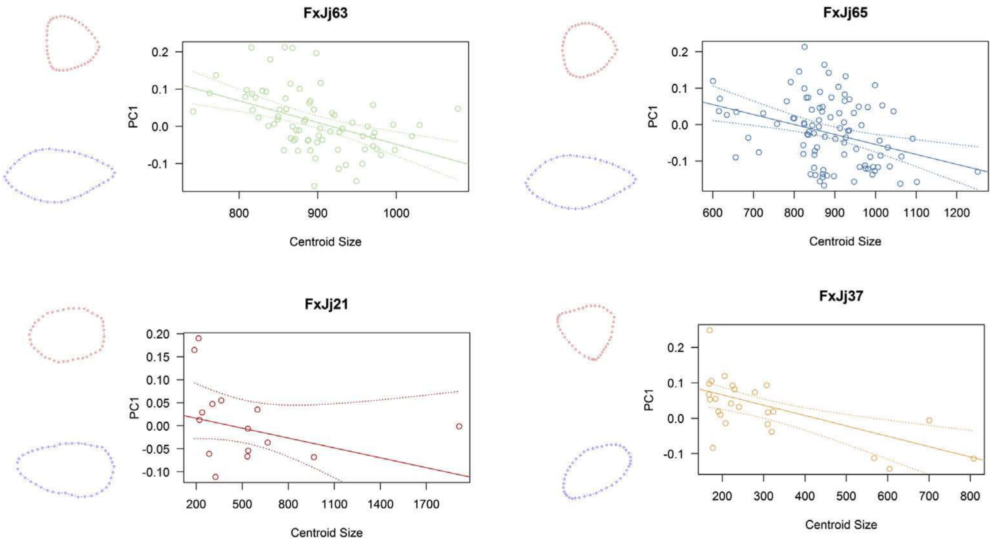

Figure 16. Principal component 1 of shape variation versus centroid size for each archaeological site. The dotted lines show 95% confidence intervals of the model (solid line).

Table 4
The estimates and standard errors for the linear model on the archaeological data. The linear model is the following: PC1 ~ edge angle (CV) + Centroid size + archaeological site. Edge angle (CV), centroid size are test predictors, while archaeological site (group) here is a control predictor.

Effect[b]	Estimate	SE	t	P	Lower CI	Upper CI
Intercept	−0.002	0.021	[a]	[a]	−0.043	0.039
Edge angle (CV)	0.014	0.006	2.435	0.016	0.003	0.026
Centroid size[c]	−0.036	0.006	−5.756	0.000	−0.049	−0.024
Group FxJj37	−0.004	0.026	−0.169	0.866	−0.056	0.047
Group FxJj63	0.024	0.023	1.006	0.316	−0.023	0.070
Group FxJj65[d]	−0.011	0.023	−0.493	0.622	−0.056	0.034

[a] Not shown because of not having a meaningful interpretation.
[b] Covariates edge angle (CV) and centroid size were z. transformed to a mean = 0, and sd = 1.
[c] Square root transformed prior to z-transformation.
[d] Group FxJj21 is the intercept.

change at FxJj63 and FxJj65 look extremely similar (Fig. 16). Both sites have marginally reduced LCTs, which resemble the original shape of the blanks (Fig. 16). These minimally reduced specimens have high values of PC1 and large centroid sizes, and often have centripetal removals. At the other extreme of PC1 are elongated specimens with marginal removals along their edges, which resemble large pick-like LCTs. A small number of discoid-like, reduced LCTs have higher values on PC1 and smaller centroid sizes. The changes from marginally reduced large flakes to elongate LCT forms are not correlated with substantial changes in centroid size.

The LCT forms at FxJj37 represent different fragments of LCT life history. The FxJj37 site has LCTs with relatively large centroid sizes and smaller PC1 values (Fig. 16). These specimens generally have rounded forms with centripetal removals. The specimens at the opposing shape extreme of this particular site are smaller and appear to be heavily reduced. Importantly the initial flake blanks as well as the elongated stage of LCT life history are missing from FxJj37. At FxJj21, centroid size does not predict PC1 well, possibly due to the majority of LCTs at this site being in heavily reduced form (Fig. 16). The major axis of shape variation at this locality represents the transition from elongated, predominantly bifacial LCTs to substantially reduced ovate LCTs, covered with centripetal removals.

Broadly, at Koobi Fora there appears to be substantial inter-site variability in LCT shape which is underpinned largely by LCT reduction intensity (Fig. 17). Further, different stages of LCT life history are differentially represented at the different sites (Fig. 18). There appears to be a landscape scale compartmentalization of different stages of LCT reduction at Koobi Fora (Hallos, 2005). This spatial fragmentation of LCT reduction is illustrated by the density of differentially reduced specimens occurring at each of the sites (Figs. 17 and 18).

Minimizing the effects of reduction on the LCT shape data A MANOVA conducted on the first 12 components of adjusted LCT shape data suggests that once the effects of reduction on shape variance have been removed, the range of LCTs in each of the archaeological sites overlaps entirely ($F = 1.327$, $p = 0.10$, $df = 3$). The ranges of LCT shapes in each of the sites are significantly different from one another. However, the majority of these differences can be attributed to reduction related LCT shape variation. Consequently, when the effect of reduction on LCT shape is removed, the ranges of shapes in each of the sites overlap with one another.

5. Discussion

5.1. *LCT shape, size and inter-site variation*

In the early Acheulean at Koobi Fora, LCT shapes appear to fall on a reduction continuum which, in a general sense, resembles the model proposed by McPherron (1994). McPherron (1994) suggested that the portion of the assemblage representing minimally reduced LCTs from Cagny-la Garenne in France overlapped with LCTs from Gouzeaucourt, an assemblage wherein only minimally reduced LCTs were present. He also concluded that the overlap between these assemblages at only one stage of reduction suggested that what at the outset looked like substantially varying LCT morphologies actually represented stages in a single continuum, where ‘Pointed’ LCTs graded into ‘Ovate’ (McPherron, 1999). Although pointed and ovate forms both exist in almost all of the Koobi Fora collections analysed here, the shape changes associated with reduction appear to be similar but slightly more complex than the spectrum described by McPherron (1994, 1999). For instance at the sites of FxJj65 and FxJj63, shape variance is characterized by the shift from round and large LCTs resembling their original flake blanks to more elongated and narrow forms. However, the tail of this reduction trajectory, representing tool maintenance, is only represented at the site of FxJj65 where it is characterized by small and ovate or discoidal looking LCTs where the tip lengths of the LCTs have been reduced further through longitudinal resharpening. In this way, McPherron's (1994) reduction model explains the very late stages in LCT life histories at these sites.

At FxJj21, LCTs appear to have been discarded predominantly in the later stages of reduction, with only a small number of examples of LCTs at the initial reduction stages. As a result most LCTs at this locality are either elongate (in a quite standardized elongate form), or are heavily reduced small and ovate LCT forms. These patterns in LCT morphological variability are in agreement with independent LCT attributes such as number of removals relative to artefact area and LCT cortex coverage, in terms of what these attributes indicate about stages of LCT reduction at different sites. For example, Figures 17 and 18 indicate that in comparison to the sites of FxJj65

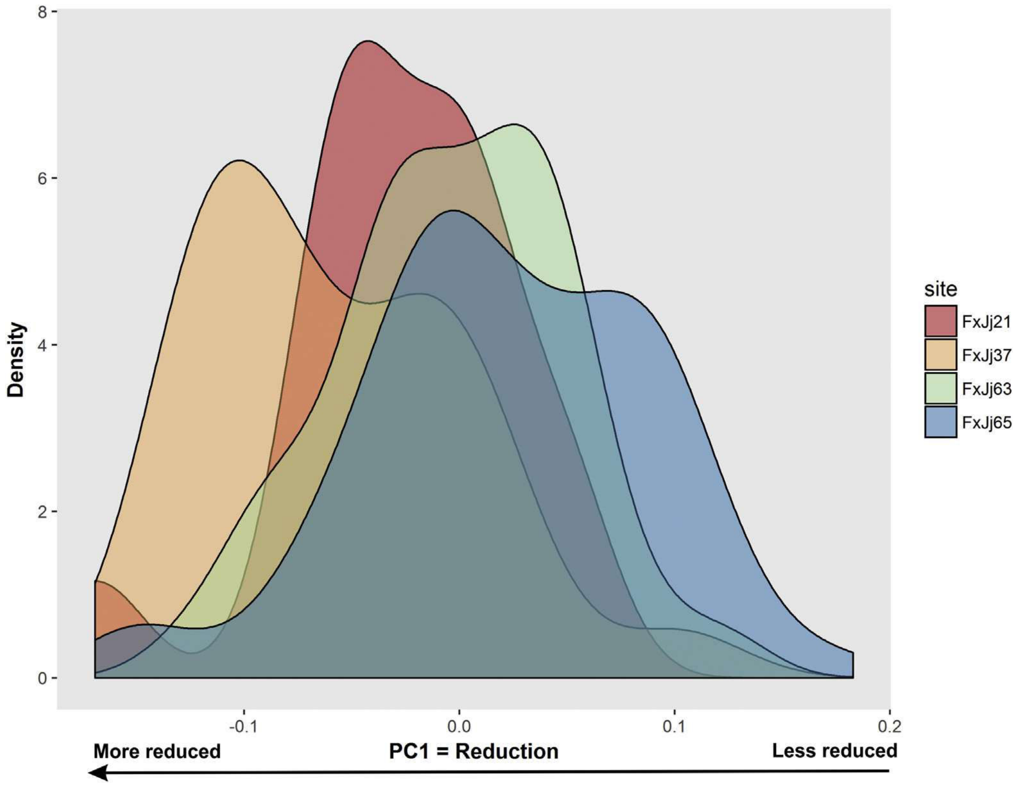

Figure 17. A density plot showing the central states of reduction (as approximated by values on PC1) for the LCTs from each of the sites. Importantly, there are two peaks associated with the density distributions of both FxJj63 and 65, the first of which (PC1 = ~0.5–0.1) is associated with large, ovate, minimally reduced LCTs. The plot was made using the ggplot2 R package (Wickham, 2009).

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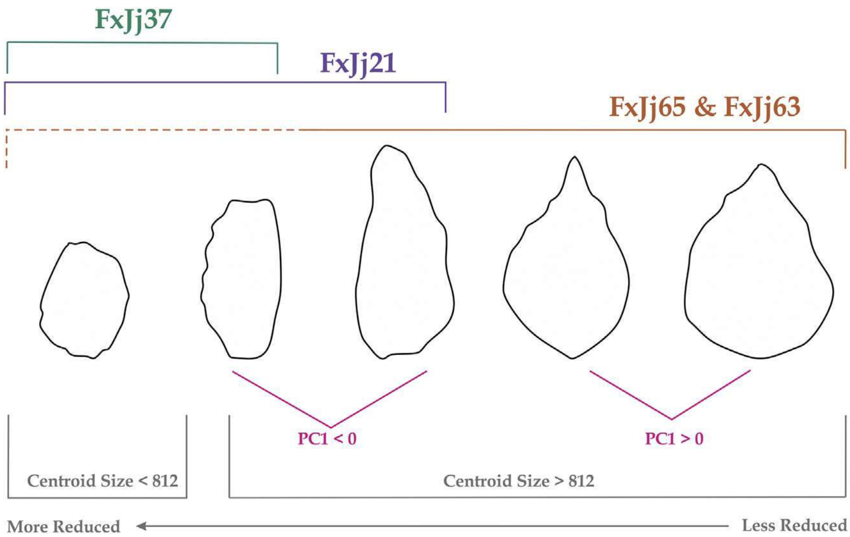

Figure 18. A schematic of shape changes for all sites at corresponding values of PC1 and centroid size Figure 17.

and FxJj63, the site of FxJj21 has more reduced LCTs. The LCTs at FxJj37 are almost exclusively small centripetal/discoidal pieces, but a small number of less intensively reduced specimens are also present. The more elongate and pointed specimens such as those at FxJj21, which probably represent some intermediate stage in LCT life history, are entirely absent at FxJj37.

Previous research has attributed centripetal and discoidal pieces in early Acheulean contexts to a chaîne opératoire which is separate from the LCT chaîne opératoire (Gowlett, 1986; de la Torre, 2009, 2011). In particular, de la Torre (2009, 2011) classified bifacial hierarchical centripetal and discoidal pieces as components of structured flaking systems which co-occurred with LCT production. However at Koobi Fora, LCT blank forms gradually grade first into elongate LCT forms and then into discoidal-like forms. Discoidal forms therefore seem to have a direct connection with LCT production strategies. Thus, when the discoidal forms at the sites of FxJj37 and FxJj65 are viewed relative to the LCT forms from the other Koobi Fora sites, it is clear that they represent one stage in a single LCT life history continuum. This continuum is differentially represented or fragmented across the four analysed sites. Therefore, when the collections from all four sites are viewed together, a coherent and continuous reduction spectrum is evident. Figure 18 represents a schematic of this inferred range and how each of the sites is represented on it.

The descriptive LCT reduction patterns suggest that most, though not all LCTs at FxJj21 and FxJj37 have centripetal removals on one or both surfaces of an LCT. The majority of LCTs from FxJj65 and FxJj63 have non-centripetal removals also on one or both surfaces, and some LCTs with non-invasive marginal removals. The 3DGM analyses provide support for the suggestion derived from the descriptive analysis that seemingly different LCT production patterns are unlikely to represent different strategies of making LCTs, but rather signify reduction stages within a single production continuum.

5.2. *Early Acheulean tool production, discard and differential site function*

Various proxies including raw material transport and discard patterns indicate that in addition to evidence for the production of LCTs, the earlier Acheulean also documents substantial shifts in the way the landscape was used by hominins (Hay, 1976). 'Site fragmentation', which refers to spatially structured artefact discard patterns, appears archaeologically as if artefact manufacture cycles at different sites have been interrupted (Hallos, 2005). In other words, fragmented assemblages represent windows onto a continuous but spatially differentiated artefact manufacture system. This phenomenon has implications for hominin mobility, site functional variation and occupation intensity (Hallos, 2005; Goren-Inbar and Sharon, 2006; e la Torre et al., 2014). Degrees of site fragmentation are also linked with planning depth abilities, which have implications for hominin cognition and working memory (Atance and O'Neill, 2001; Hallos, 2005).

In contrast to Oldowan sites that frequently have complete artefact life cycles (Semaw, 2000; Delagnes and Roche, 2005), later Acheulean sites are frequently fragmented. For example, bifacial LCTs from Kilombe and Olorgesailie in Kenya, as well as Elandsfontein in South Africa, were transported to the sites in a manufactured form, and were only re-sharpened at these sites (Isaac, 1977; Crompton and Gowlett, 1993; Braun et al., 2013; Presnyakova et al., 2015). Site fragmentation and differential discard is also evident among several contemporaneous late Acheulean sites at Mieso, Ethiopia (de la Torre et al., 2014). However thus far it has been unclear whether any early Acheulean evidence points to hominins planning their actions in clear anticipation of future needs (Hallos, 2005).

Unlike FxJj65 and FxJj63 sites with the full sequence of LCT production, it is clear that at the sites of FxJj21 and FxJj37 several stages of LCT life history are missing, and the production sequence is fragmented. Multiple lines of evidence suggest that the initial stages of tool manufacture are not present at FxJj37 and FxJj21. For instance, in stark contrast to FxJj63 and FxJj65, there is no evidence for on-site LCT blank production at FxJj37 and FxJj21, and there is a total absence of sizable cores. There is also a significant difference in the size of unworked flakes at FxJj37 (measured by both mass and volume), compared with the larger flakes which had been shaped into LCTs at the same site, suggesting that LCTs were made elsewhere. FxJj37 and FxJj21 both also have relatively low assemblage level cortex coverage, appear to have more heavily reduced LCTs than the other sites and have lower frequencies and smaller sizes of all lithic artefacts. These general characteristics are suggestive of the later stages of tool life history. Further, small numbers of finds and normal distributions of artefact sizes at FxJj37 contrasts with high numbers of finds and multimodal distributions of

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artefact sizes at the sites of FxJj65 and FxJj63. A multimodal distribution, which is extremely rare for lithic size distributions, likely results from a small component of flakes being produced as biproducts of different phases of manufacture, in addition to a range of discretely larger products associated with LCT blank production. One would expect this distribution to occur at sites where hominins were making tools or gearing up (Binford, 1979; Bleed, 1986; Bousman, 1993).

Early Acheulean artefacts at Koobi Fora were likely to have been manufactured at specific places on the landscape, such as the site of FxJj63. Further evidence for the presence of specific manufacturing localities is provided by the refitting of a large LCT blank to the core from which it was struck at FxJj63, in addition to the frequency of LCTs at this same locality which had been abandoned after only a small number of removals (see SOM Fig. S7). Large cutting tools were then transported by hominins away from these LCT manufacturing localities, and were resharpened and discarded in different places on the landscape, such as at the localities of FxJj37 and FxJj21.

Here, using data on (a) LCT production and discard patterns, (b) artefact cortex coverage, (c) proxies for tool reduction such as adjusted scar counts and (d) artefact frequencies and size distributions, we demonstrated that even at the earliest stages of the Acheulean hominins were using a highly mobile technological system. In this way, early Acheulean sites from Koobi Fora echo the pattern of hominin landscape use described for the late Acheulean site of Mieso (de la Torre et al., 2014). Whether spatially fragmented artefact production systems occur at other early Acheulean localities is a question which needs to be addressed in future research.

5.3. Site fragmentation and landscape use patterns

Several variables could potentially have shaped the role that different sites on the landscape played as focal points for hominins to either make or use stone artefacts (Potts et al., 1999). There may have been a multivariate network of drivers that influenced the tendency for hominins to discard their tools, which are not necessarily exclusionary of one another. Since raw material is homogeneous across all the sites investigated in this study, the most parsimonious explanatory variable to account for the documented patterns of site fragmentation may be the distance between the various localities and raw material sources. Distance to raw material sources is a well-established driver of artefact variability in the Early Stone Age (Blumenschine et al., 2008). This may have affected hominin mobility patterns and, contingently, artefact morphological variability and typological compositions, as well as densities in assemblages from different sites (Féblot-Augustins, 1993; Potts et al., 1999; Blumenschine et al., 2012).

At Koobi Fora, the Gombe Basalt was deposited during the Pliocene, and was a critically important source for stone tool production from 1.5 to 1.39 Ma (Braun et al., 2009a; Bruhn et al., 2011). Table 5 shows the distance of the sites analysed here to this source of raw material (see also Fig. 1). Interestingly, the minimum distances from the sites to the basalt outcrop do not match our expectations. We are not able to use distance from raw material source to make predictions for tool reduction intensity at the different sites analysed here. For instance, the site of FxJj37, which has the most extensively reduced LCTs, is in fact the closest site to the Gombe basalt outcrop, and the tool manufacturing sites of FxJj63 and FxJj65 are unexpectedly much further from the basalt outcrop than FxJj37.

Table 5
Approximate distances from individual sites to the basalt outcrop.

Site	Distance to the basalt outcrop
FxJj21	~4 km
FxJj37	~3 km
FxJj63	~7 km
FxJj65	~7 km

The Karari Industry, often referred to as 'Developed Oldowan', dates to ~1.5 Ma and is slightly older than the early Acheulean assemblages discussed in this study (Harris and Isaac, 1976; Braun et al., 2008a). Karari assemblages from the same geographic region as the early Acheulean sites discussed here indicate that hominins clearly adjusted their artefact procurement and discard patterns in response to raw material procurement opportunities (Braun et al., 2008a). Our findings suggest that ~110 thousand years later than the Karari Industry, early Acheulean hominins at Koobi Fora appear to have produced, resharpened and discarded their tools in response not only to raw material availability but also other environmental variables such as habitat preference and dietary resources (Quinn et al., 2013; Patterson et al., 2017). However, sufficient independent data are not yet available to test these ecological explanations quantitatively with our early Acheulean dataset. Our reconstruction of early Acheulean artefact discard patterns relative to known sources of raw material suggests a disparity in landscape use and mobility patterns between Oldowan and Acheulean tool producing hominins. Hay (1976) previously suggested similar differential patterns of landscape use between Oldowan and Acheulean associated hominins at Olduvai Gorge (Hay, 1976). Such differential landscape use, at least at Koobi Fora, may well have been associated with new subsistence opportunities, made available through the adoption of Acheulean technologies. However, we cannot entirely discount the possibility that secondary raw material sources were available when the early Acheulean sites in Koobi Fora were occupied, which may have not yet been identified, or which are no longer visible on the landscape today. Ongoing detailed studies of the environments associated with these sites may enable the evaluation of this possibility in the future.

6. Conclusion

Previous research has focused on the archaic or crude nature of earlier Acheulean biface industries, which are suggested to have evolved into later more 'refined' and symmetrical bifacial forms (Beyene et al., 1997, 2013; de la Torre et al., 2008; Lepre et al., 2011). Specifically, Stout (2011) suggested that the complex hierarchy of actions entailed in LCT manufacture only initiated in the late Acheulean, ~700–500 ka. Various researchers have advocated a set of characteristics including bifacial and bilateral symmetry, the removal of trimming flakes and the use of a soft hammer and platform preparation, all of which characterize late Acheulean bifaces and signify enhanced cognitive abilities (Wynn, 1985; Foley and Lahr, 2003; Roche, 2005; Beaumont and Vogel, 2006; Stout et al., 2014). Although we do not disagree with these suggestions, we show here that when multiple contemporaneous early Acheulean localities are analysed together, and a relatively broad window on LCT variability is documented, a complex and variable set of LCT forms are revealed to exist at a very similar point in time. These forms range from typically crude and asymmetrical early Acheulean LCTs to relatively refined and symmetrical pieces. In the absence of chronological context, these refined pieces could conventionally be assumed to be more characteristic of later bifacial industries. We demonstrate that this range of LCT shapes falls on a single early Acheulean reduction trajectory for all of the four sites, wherein substantially varying forms blend gradually into one another. Moreover, our data suggest that the early Acheulean sites in Koobi Fora were spatially fragmented. We interpret this fragmentation as the consequence of site functional variability and

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differential landscape use by hominins, which may be reflective of unexpectedly in depth planning abilities (Hallos, 2005). Whether early Acheulean hominins had evolved these abilities by ~1.4 Ma remains an open question to be further confirmed with future research.

Conflicts of interest

None.

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Supplementary Online Material

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Appendix III.

Considerations in the application of 3DGM to stone artifacts with a focus on orientation error in bifaces

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Abstract

Stone artefacts are the most abundant vestiges of hominin behaviour for much of human evolutionary history. Our understanding of the relevance of stone artefacts to human behavioural evolution is driven largely by our ability to document and analyse stone artefact form (artefact size and shape). 3DGM (3-Dimensional geometrics morphometrics) offers a set of high-resolution statistical shape analysis tools, traditionally used in biological studies, which are potentially useful in this endeavor. However, 3DGM has thus far only been applied successfully to a limited range of stone artefact forms. Due to the unique morphological characteristics of stone artefacts and the substantial variability within many tool types, there are a number of potential pitfalls in adapting 3DGM for usage in stone artefact analyses. In this chapter, some basic considerations in the application of 3DGM to stone artefacts are discussed. The issue of artifact orientation poses a significant and unique hurdle in stone artefact forms with few geometrically correspondent features, and is thus given special attention. An assemblage of landmark configurations of bifacial tools (points or handaxes) is simulated. Portions of this assemblage are then manipulated in terms of their orientation, in order to illustrate the potential effects of orientation error when applying 3DGM to actual archaeological assemblages.

Introduction and background

Variability in stone artefact form provides the foundation upon which interpretive frameworks in lithic studies are built. Three-dimensional approximations of stone artefacts, such as outlines and landmark configurations, afford a more detailed means of documenting variability in both artefact shape and size than traditional linear measurements (Shott and Trail 2010). Such three-dimensional approximations document systematic but subtle aspects of stone artefact variability that may not easily be visible to, or measurable by, lithic analysts. The powerful statistical tools of 3DGM (Three-Dimensional geometrics morphometrics) are useful relative to traditional linear measurements of stone artefacts, as the latter will almost always be correlated with overall artefact size (Bookstein 1997). 3DGM, however, enables the retention of information regarding the geometric covariation between large numbers of landmarks on a given artefact, in all steps of analysis. The retention of these complex relationships is generally not possible with linear measurements as the majority of these measures, such technological length, width or thickness, are not measuring distances between geometrically homologous features on stone artefacts, and therefore capture the combination of both artefact size and shape together (Ioviţă 2010).

The combination of benefits offered by 3DGM opens the potential for documenting behaviours associated with past stone artefact manufacture at higher resolution than has been possible within conventional lithic analyses. It is worth mentioning that in recent years, the number of available instruments for applying 3DGM within stone artefact analyses has increased substantially. The freedom afforded by statistical platforms like R to adapt one's workflows flexibly to the specific features of different artefact forms is useful, if not essential, to developing reliable 3DGM stone artefact routines (Schlager 2013, Archer, Pop et al. 2017).

The adaptation of 3DGM approaches for usage in stone artefact analysis, however, poses several challenges. These arise in comparison with their traditional application in biological research. Unlike many biological organisms, stone artefacts have very few homologous features. Consequently, the analysis of stone artefacts using geometric morphometrics was generally not feasible until the relatively recent development of applying semi-landmarks to document curves and surfaces on specimens where homologous landmarks are rare or absent (Bookstein, 1997; Gunz, Mitteroecker, & Bookstein, 2004; Mitteroecker, Gunz, Bernhard, Schaefer, & Bookstein, 2004; Slice, 2007). Using semi-landmarks, it is possible to analyse stone artefact types that have technologically or functionally homologous axes in the absence of clearly homologous features (Archer, Pop et al. 2018, Presnyakova, Braun et al. 2018). Some artefact types such as "cores" remain complicated to analyse accurately with 3DGM due to the lack of technologically homologous axes available to orient them. For instance, unlike bifacial tools, developing an orientation protocol for cores is challenging, as there is no directional axis to determine the distal or proximal zones.

Raw data capture

Before conventional transformations (e.g. Generalized Procrustes analysis) can be undertaken with stone artefact landmark data, several additional issues require attention in the raw-data collection phase. At the outset one is faced with the task of raw data acquisition which entails largely the scanning or the generation of structure from motion 3D models of stone artefacts. This process involves selecting a method that is both sufficiently detailed to capture the characteristic features of a selected stone artefact type, and is efficient in the time required to scan a sample of specimens.

The majority of 3DGM studies on stone artefacts rely on surface scanners to obtain meshes to analyse. Three properties of stone artefacts that cause difficulties for most surface scanners are (a) the transparency, and (b) the reflectivity of the raw-materials being scanned, as well as (c) the acuteness of the angles of the targeted artefact edges. In this vein, translucent and glossy raw-materials such as quartz and obsidian can be particularly challenging to scan. Low edge angles on thin artefacts such as blades can further perpetuate the scanning issue. Thus, artefacts with problematic properties can take longer to scan effectively, and generally require more post-processing steps; for instance the filling of holes on mesh surfaces, the reversing of inverted face normals, and the removing of unreferenced and duplicated vertices. Post-processing steps such as filling holes generally increase the error between the mesh and the morphology of the artefact that is approximated by the mesh. Different coating powders are often provided with the purchase of surface scanners or can be replaced by talcum powder. These powders can be brushed onto the surfaces of objects, and are intended to make these surfaces less reflective and therefore easier to scan. However, coating raises the possibility of contaminating archaeological materials such as residues on tool edges, and therefore is recommended only for experimental (non-archaeological) assemblages. In situations where 3D analysis is not feasible, 2D geometric morphometrics using artefact image analysis may be a suitable alternative (Buchanan and Collard 2007, Buchanan and Collard 2010, Monnier and McNulty 2010).

Artefact Orientation

After scanning, artefact meshes need to be digitized to produce configurations of coordinates or 'landmarks'. It is critical, however, that all stone artefacts are oriented in three dimensions prior to landmarking. This is the case even if 2D in contrast to 3D geometric morphometric analysis is intended. Orientation of artefacts in 3D is sometimes overlooked by archaeologists in the analysis of artefact types that have few geometrically correspondent features, such as Handaxes and most bifacial point types (hereafter 'bifaces'). Bifaces have only tips and, occasionally, bases on which 'fixed' - i.e. immovable - landmarks can be placed. Flakes, on the other hand, are more complex forms that have distinctive dorsal, ventral, and platform surfaces that can guide the placement of landmarks on geometrically correspondent corners and curves at the intersections of these three surfaces (Archer, Pop et al. 2017).

The vector linking the tip and the base of bifaces, i.e. the points between which one would typically measure biface length, is often considered a first axis of orientation for specimens in a sample of bifaces (McPherron and Dibble 1999, Archer and Braun 2010, Archer, Pop et al. 2016). Yet, to make other semi-landmarks on bifaces - such as those on the edges and surfaces - comparable across all specimens, orientation requires a second step. Bifaces need to be oriented in a second orthogonal axis before edge landmarks can be digitized, and further, edge landmarks need to be ordered in the same sequence on all specimens once they have been oriented along this second axis (Archer, Gunz et al. 2015). A conventional approach to this issue for biface orientation is to ensure that the more convex face, or the face with more cortex always faces the same direction relative to the placement of individual landmarks (Lycett, von Cramon-Taubadel et al. 2006, Archer, Gunz et al. 2015). The two surfaces of heavily reduced bifaces though may not retain any cortex, but they invariably differ in volume. It is discussed below that one method of orienting certain artifacts such as bifaces is to use Principal Components Analysis ('PCA').

If one skips the second orientation step discussed above, subsequent landmarks placed on tool edges will not correspond geometrically between specimens, and therefore will not be comparable across specimens. In such incorrectly orientated assemblages the shape variance that is apparent on a PCA, for example, can as easily be underpinned by orientation error as by the hominin behaviours in which we are interested (i.e. when opposing edges and surfaces are being compared as correspondent features between incorrectly and correctly oriented specimens). To illustrate this potential influence of orientation error on geometric morphometric analyses, here, edge landmark configurations of an assemblage of 1000 bifaces are simulated. These simulated bifaces vary substantially in terms of their lengths and widths. Further, the shapes of the biface edges are modified by fitting Bezier curves to each individual specimen, using a sub-set of the edge landmarks as control points (Olsen 2014).

Within this simulated dataset, randomly selected cases (sets of individual bifaces) can be selected, and can be bilaterally inverted i.e. they can essentially be reflected, a procedure which will hereafter be referred to as 'mis-orientation'. This specimen-by-specimen procedure is analogous to taking an archaeological biface that is correctly oriented, for example, and flipping it over onto its opposing face before digitizing it. Importantly, the effects of mis-orientation on assemblage level biface variability can then be visualized with a bivariate plot of specimen scores from a PCA. In the following paragraphs, the potential consequences of mis-orientation will be explored in this simulated assemblage of bifaces.

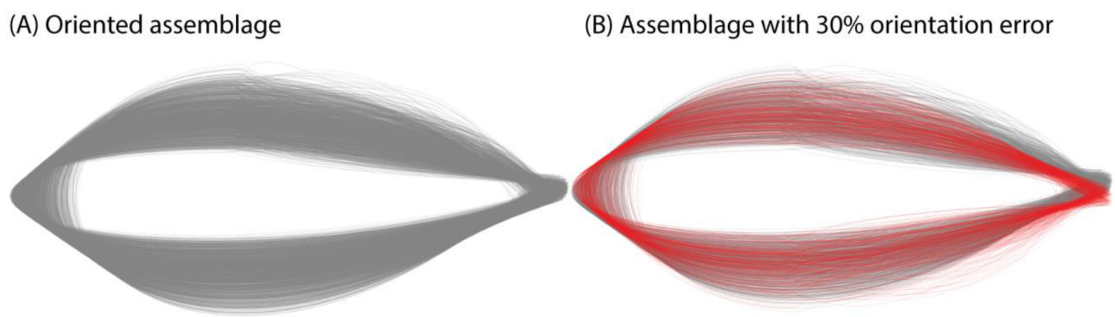

Figure 1: The simulated assemblage of 1000 biface edge outlines adjusted for size with Procrustes superimposition, for the original simulated assemblage (A) and the simulated assemblage with added orientation error shown in red (B).

This simulation approach allows one to investigate the effects of orientation error on aspects of asymmetry in an assemblage where one knows exactly what the variation should look like (Figures 1(A) and 2). Specifically, a biface assemblage with directional edge asymmetry was generated (note the variability in the upper edges of specimens on Figure 1(A)). Shape variation associated with edge asymmetry is a feature of variability one would expect to be particularly susceptible to the effects of orientation error. One would expect such variation in bifaces where the functional edge, for example, tends to have the same three-dimensional position relative to other geometric features, such as “Keilmesser” (Weiss, Lauer et al. 2018). In actual archaeological assemblages, where there may be substantial noise in the data, systematic asymmetry in bifaces tends to be more subtle. This simulation is therefore an example of the effects of mis-orientation on an assemblage wherein asymmetry is perhaps unrealistically visible.

To outline the differences between correctly oriented and mis-oriented specimens, an Elliptical Fourier Analyses (‘EFA’) was conducted on the simulated assemblage using functions available in the Momocs and sp R packages (Pebesma and Bivand 2005, Bonhomme, Picq et al. 2014). EFA is a method of decomposing closed curves into sets of coefficients that cumulatively estimate closely, for example, a given artefact shape or set of artefact shapes. The coefficients correspond to harmonics which approach actual artefact shape more closely with each added harmonic. EFA has been used in the analysis of biface and flake shapes (Ioviţă 2009, Ioviţă 2010, Iovita 2011, Iovita and McPherron 2011, Rezek, Lin et al. 2011, Archer, Pop et al. 2016).

A PCA of elliptic Fourier transformed coefficients was then visualized to display the major axes of variation in the simulated assemblage, showing the correctly oriented data first (Figure 2). As is the case with many biface collections, the variation between ovate forms and elongate forms is represented along PC 1 (i.e. biface elongation: ~91% variance). Systematic "upper-edge" shape variation (or asymmetry) appears to be represented on PCs 2 and 3 (8.65% and 0.92% variance: Figure 3 (A)).

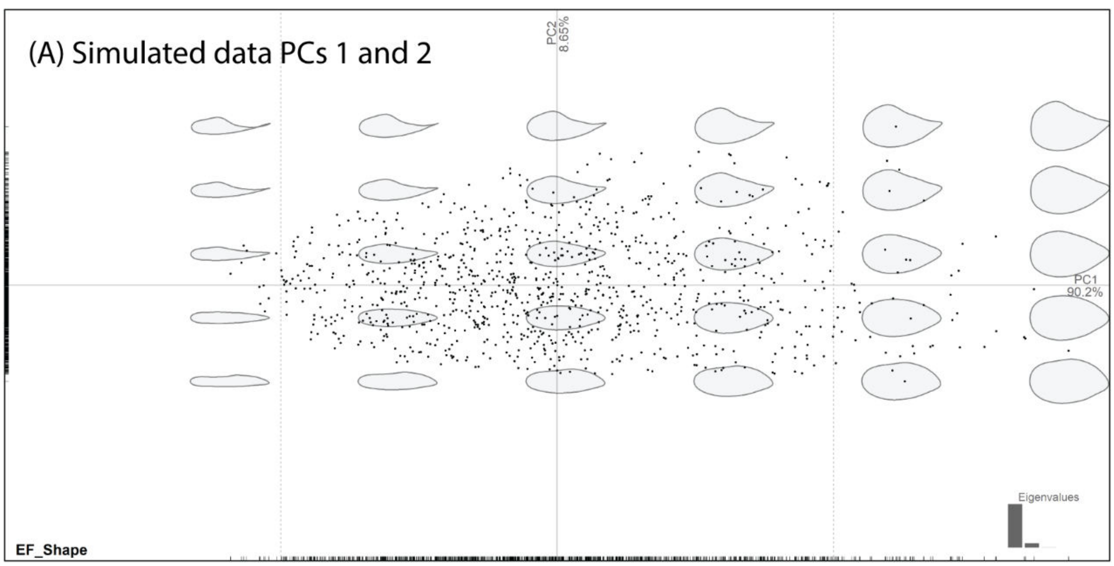

Figure 2: Principal components 1 and 2 of the first 8 harmonic coefficients, showing the structure of variability of the correctly oriented simulated biface assemblage.

Randomly selected samples of cases were then drawn iteratively from this sample of 1000 bifaces, and their edges were inverted (i.e. they were mis-oriented). This inversion was undertaken on samples of cases at 2.5% size intervals (i.e. first n=25 cases, then n=50 cases, then n=75 cases etc.). These intentionally mis-oriented specimens were returned back into the overall assemblage, and the effects of mis-orientation on the major components of shape variation were assessed with PCA at each interval.

Importantly, with only 2.5 % mis-oriented specimens in the dataset, the distribution of cases on the PCA already looked substantially different (Figure 3 (B)). By the stage at which ~33% of the simulated bifaces had been mis-oriented (n=325 cases), the proportion of variance accounted for by asymmetry on PCs 2 and 3 had dropped to negligible amounts (0.59% and 0.1%) and the distribution of specimens on the PCA looked nothing like the distribution of specimens in the correctly oriented assemblage (Figure 3 (C)).

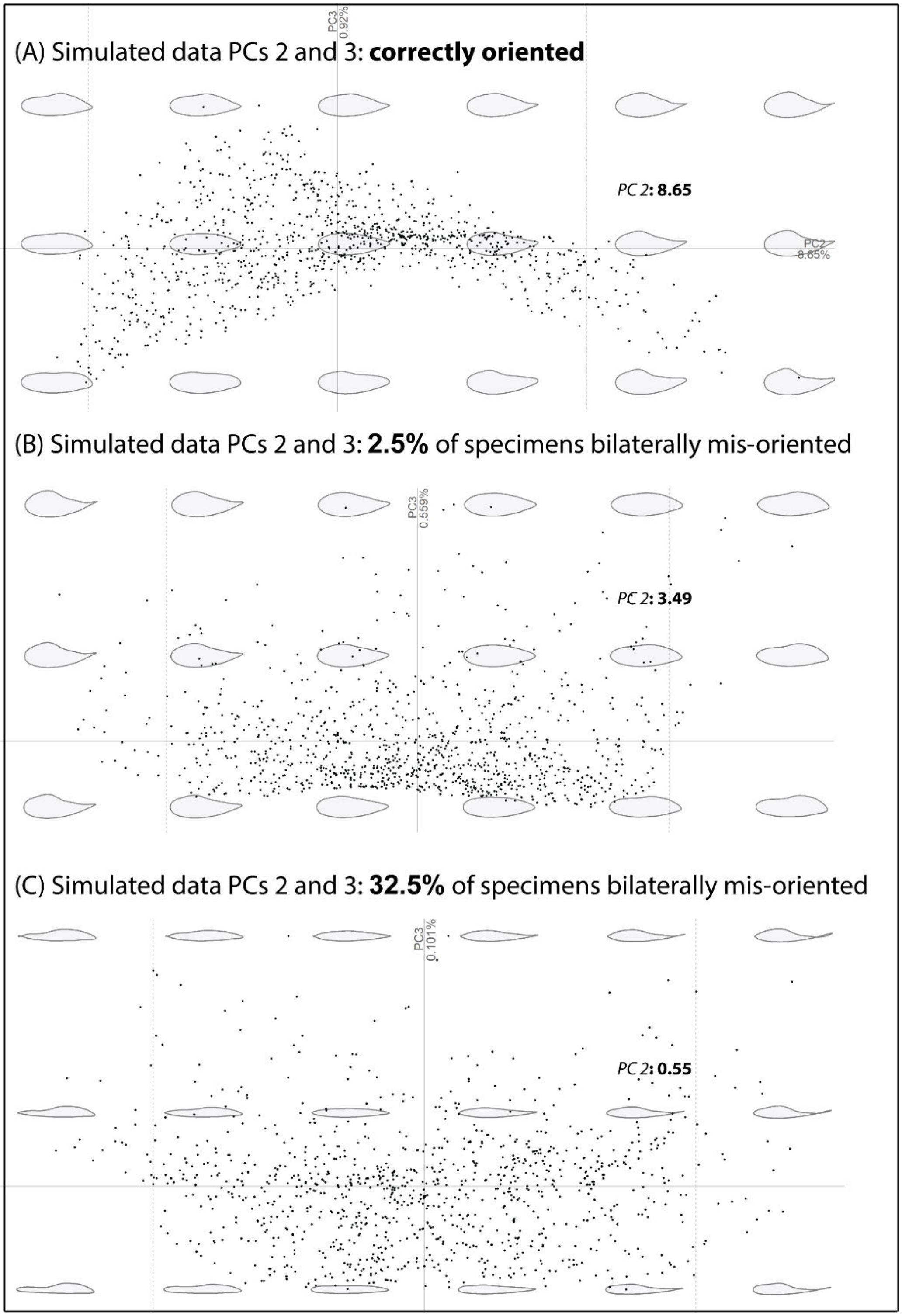

Figure 3: Biface shape variation on Principal Components 2 and 3 for (A) the assemblage of correctly oriented specimens, (B) the assemblage with 25 specimens bifacially inverted or 'mis-oriented' and (C) the assemblage with 325 specimens bifacially inverted.

Our simple experiment demonstrates how even marginal artefact orientation error (small numbers of incorrectly oriented specimens) can have substantial effects on assemblage level shape data. These effects can potentially hide behaviourally meaningful aspects of variability, such as the variation underpinning edge asymmetry in this particular example. In geometric morphometric studies of stone artefacts, initial orientation is therefore an important consideration at the early stages of data collection (scanning or photographing and landmarking), and is generally difficult to correct retrospectively.

To avoid orientation errors such as the one illustrated with the simulated assemblage above, it is important to orient bifaces in two orthogonal axes (as opposed to just one e.g. the bilateral axis of symmetry). It is additionally important to ensure that one biface surface is oriented (i.e. is facing) in the same direction on all specimens, before the edges are landmarked. As mentioned already, one approach to establishing this opposition uniformly across all specimens is to ensure, firstly, that the most convex surface in every specimen faces the same direction in bilateral plan prior to landmarking. Secondly, that edges are always landmarked in the same order (e.g. starting at the tip and proceeding in a clockwise direction along the edges) on all specimens. As many bifacial tools are more-or-less bifacially symmetrical, determining which of the two faces is the more convex (i.e. which surface encompasses a greater volume of stone) may not be a trivial task. It is useful therefore, although not essential, to automate such orientation considerations (Archer, Gunz et al. 2015) (Figure 4).

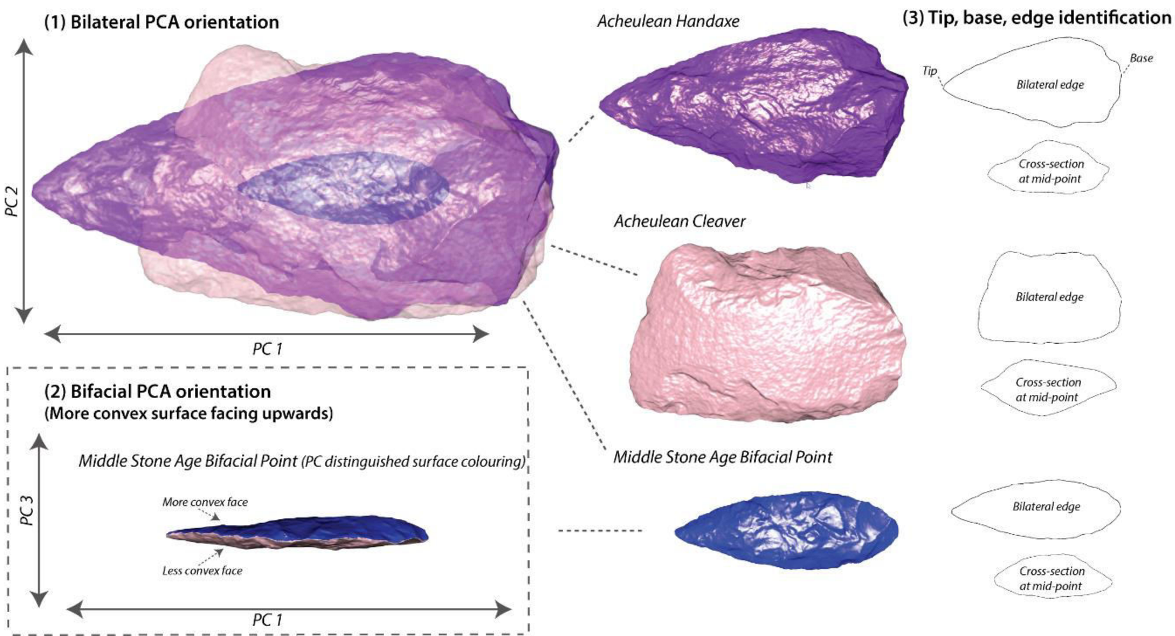

Figure 4: Scans of a Handaxe and a Cleaver from the Acheulean deposits at Montagu Cave (1), and a 'Still Bay' bifacial point from the Middle Stone Age site of Blombos Cave (2). Both sites are in South Africa. (1) A plot of the scores of artefact mesh vertices on PCs 1 and 2. (2) A plot of the mesh vertices on PCs 1 and 3 demonstrating that artefact bifacial orientation can, if needed, easily be modified by inverting the scores of vertexes on PC 3. (3) Polygons of the automatically extracted biface edge landmarks in plan-view as well as in cross-sectional view.

PCA is a useful tool for orienting automatically the meshes of certain artefact types, such as bifacial tools, in terms of homologous orthogonal technological axes (i.e. Principal Components) (Figure 4). Artefact meshes saved as Polygon File Format 'PLY' are made up of vertices (points with XYZ coordinates); information on how these vertices are linked up into polygons, and vectors indicating the direction in which these polygons are facing (so-called 'normals'), which together approximate an artefact's surface. Using PCA for mesh orientation entails undertaking a PCA on the XYZ coordinates of the vertices of each individual mesh in a sample. One can then take the XYZ coordinates of the vertices in PCA space (the PC 1-3 scores for each vertex) and write these PC 1-3 scores, along with the other mesh information (polygons, normals), as a newly oriented PLY file that can be used in subsequent steps of a workflow. See Archer et al (2015) for a detailed overview of this orientation process being applied to Middle Stone Age bifacial points.

PCA generally identifies the technological length axis of bifacial tools as the first component of variation, and the edge-to-edge width(s) as the second component (i.e. 'PC2'). Similarly, Principal Component 3 ('PC3') identifies the variance in bifacial tool thickness, which is approximated by the distance between the two faces of an individual tool. The variance in vertex scores along PC3 can be used to evaluate which of the biface surfaces is more convex on each specimen. In addition, the scores for vertexes on PC3 can then be inverted, if required, so that the most convex surface is oriented in the same direction on all specimens.

PCA also makes the automatic identification of tool tips, bases and edges possible in accordance with geometrically correspondent Principal Component axes (Figure 4(3)). For instance, one can identify biface tips and bases simply by looking at the differences between individual vertex scores along PC1. Secondly, in a bivariate plot of vertexes on PCs 1 and 2, a concave hull will identify the entire tool edge accurately on the majority of bifaces.

Placing Landmarks

As mentioned already, most stone artefact types have very few homologous features in comparison with biological organisms. A central challenge in applying geometric morphometrics to stone artefacts, therefore, is the paucity of geometrically correspondent locations available upon which landmarks can be placed. In this vein, stone artefacts generally need to be digitized using the combination of a small number of fixed landmarks on clearly identifiable common features, and many more semi-landmarks in between these common features. It is important that these fixed landmarks do not move in subsequent steps of any workflow. Examples of reliable fixed landmarks are the tip and base of bifacial points, or the point of percussion on flake platforms (Archer, Gunz et al. 2015, Archer, Pop et al. 2017).

Semi-landmarks can then be placed on ‘curves’ such as geometrically correspondent stone tool edges, as well as on ‘surfaces’ such as flake ventral and dorsal surfaces. Semi-landmark placement on curves relies on previously placed fixed landmarks in-between which these semi-landmarks can slide. These semi-landmarks on the curves of stone artefacts equate largely to coordinates on artefact edges. For instance, the semi-landmarks on one edge of a biface might slide along that edge between the tip and the base (Figure 5).

As stone artefacts often are highly variable in overall shape, even in a single type of stone tool such as a biface, some specimens within a given assemblage will have relatively more complex edges than others do. It is important that these relatively more complex edges have higher initial numbers of points approximating them than do edges that have a more homogeneous shape. The points initially digitized on stone artefact edges thus serve the purpose only of delineating a vector along which the final (resampled) semi-landmarks will be positioned (Figure 5 (B)). If this vector is represented by points too few relative to the complexity of a particular edge, then semi-landmarks could ‘slip off’ the edge and onto an artefact surface during resampling, an accident that could introduce substantial error into a dataset. There are a number of functions in the Morpho and Geomorph R packages which will undertake resampling and also the sliding of semi-landmarks on stone artefact edges (Adams and Otárola-Castillo 2013, Schlager 2013).

Placing landmarks on artefact edges may well capture sufficient data to address a particular research question. However, where shape variance is driven more by features of artefact surface morphology - such as an assemblage of flakes wherein variability in the morphology of the bulbs may be important - additional landmarks may be useful (Archer, Pop et al. 2017). In such an application, the placement of additional landmarks on flake ventral and dorsal surfaces, for example, may be required (see Figure 5 (C) for an example of surface landmarks in bifacial points).

The procedures needed to place landmarks on artefact surfaces rely heavily on the accurate prior placement of landmarks on the artefact edges. One method of placing landmarks on stone artefact surfaces entails first manually landmarking the surfaces of a single randomly chosen template specimen. It should not matter which specimen in an assemblage is selected to be this template. A biface template may for example comprise a configuration of one fixed point on the tip, one fixed point on the base, a set number of evenly spaced landmarks on each edge and a set of manually placed landmarks on each of the two surfaces.

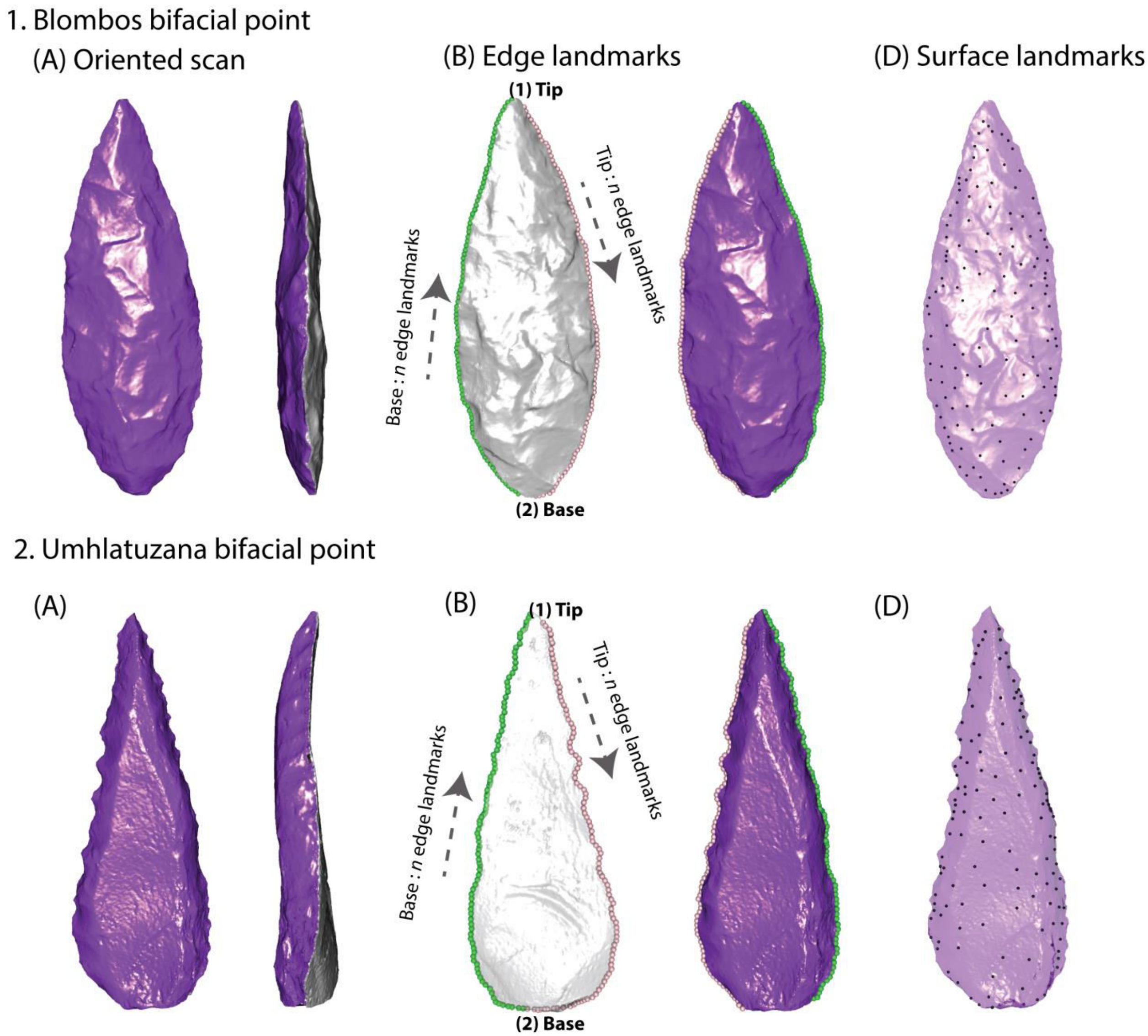

Figure 5: Examples of landmark configurations of two different morphologies of Middle Stone Age bifacial points, dating 77-70 ka, from the sites of Blombos Cave (1) and Umhlatuzana (2) in South Africa. (A) shows the meshes with the two faces segmented, illustrating the more convex (purple) and the less convex (grey) surface in different colors. (B) illustrates the landmarks along the two edges in different colors, which are separated by the tip and base. (C) illustrates the surface landmarks on the more convex bifacial surface.

The template configuration of landmarks can then be deformed or 'warped', iteratively, onto each of the surfaces of the other bifaces in that assemblage (the 'target' specimens). The purpose of this deformation is to approximate the positions of the corresponding surface landmarks on each of the target specimens that, up to this stage, are absent on every specimen but the template. This deformation can be challenging, depending on how variable the morphology of the assemblage of target specimens is, and it can be computationally slow if many surface landmarks are required. The R package 'Morpho' describes a series of functions that are extremely useful for undertaking surface landmarking in a stone artefact analysis context (Schlager 2013).

Conclusion

3DGM offers a powerful set of tools for lithic analysis, which are being adopted by archaeologists at a rapidly increasing rate. The ability to capture artefact form with landmarks facilitates an unprecedentedly resolved description of artefact shape. Using these landmarks, the tools of 3DGM enable lithic analysts to document the complex covariation between large numbers of artefact features in all steps of analysis, to treat the properties of artefact size and shape entirely separately, and to isolate the relationships between different aspects of artefact shape and size. As all phases of stone tool manufacture and maintenance are inherently reductive, the ability to map detailed allometric trajectories in different technologies is of great importance to understanding past hominin behaviours.

Currently, the use of 3DGM is inhibited by the time-efficiency of available scanning technologies, and the feasibility of landmarking large collections of stone artefacts. Yet the rapidly increasing capacity of scanning technologies, and the possibility of developing automated landmarking protocols, is making the option of 3DGM more and more feasible in wider ranges of lithics assemblages and archaeological questions. As the simulated example above demonstrates, however, using 3DGM blindly, even in assemblages of relatively simple forms like bifaces can quite easily result in error-strewn results. While orientation error, for instance, may have limited effects on certain assemblages, it has the potential to significantly blur behaviourally meaningful variance in others.

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