Ecological perspectives on technological diversity at Kanjera South

Jonathan S. Reeves[*,a,1], David R. Braun[b,1], Emma M. Finestone[c,1], Thomas Plummer[1,1]

[a] *Eberhard Karls University of Tübingen, Schloss Hohentübingen Burgsteige 11, 72070 Tübingen, Germany*
[b] *George Washington University, 800 22nd Street, North West, Washington D.C., USA.*
[c] *Max Planck Institute for the Science of Human History, Kahlaische Strasse 10, D-07743, Jena, Germany*
[d] *CUNY & NYCEP, 65-30 Kissena Blvd, Flushing, NY 11367, USA*

Abstract

The aspects of hominin behavior responsible for Oldowan stone tool variation has been the focus of much debate. There is some consensus that Oldowan artifact variation arises from a combination of ecological and cultural factors. These factors are often examined independently of one another. The diversity of raw material types and technological strategies present at the site of Kanjera South provide an opportunity to examine the interacting effect of ecology and culture on Oldowan stone tool variation. Here we combine previous analyses of raw material properties, provenance, and technology with quantitative measures of core reduction intensity and tool utilization to examine the influence of both ecological and techno-cultural factors on stone tool variation at Kanjera South. The results of this analysis show that technological variation at a Kanjera South reflects a dynamic relationship between raw material properties, provenance, and hominin mobility. Cores produced on raw materials from distant sources are more reduced than locally sourced raw materials. Distant raw materials are generally more resistant to edge attrition compared to those available locally

*Corresponding Author
Email addresses: jonathan.reeves@uni-tuebingen.de (Jonathan S. Reeves), David_Braun@gwu.edu (David R. Braun), finestone@shh.mpg.de (Emma M. Finestone), derek@example.com (Thomas Plummer)

which may have incentivized their transport over long distances. Moreover, the variation in stone tool reduction is not constistent with neutral models of stone tool transport and discard. This suggests that the lithic assemblage at Kanjera South may reflect a structured land-use strategy that may relate to the resource rich nature of the Homa Penninsula. This pattern of stone tool utilization also has an impact on the technological strategies employed by Oldowan tool makers at Kanjera South. Cores produced on raw materials from distant sources also exhibit more complex core reduction strategies than locally acquired materials. While this pattern is partially due to the differences the quality of knappable stone, bifacial centripetal and multifacial core reduction strategies also arise due to the continuous transport and use of exotic raw materials. These results demonstrate that ecological factors such as raw material provenance and physical properties have strong impacts on reduction intensity and the technological strategies utilized by hominins. Yet, not all stone tool variation at Kanjera South can be explained by this relationship. These results suggest that Oldowan stone tool variation should not be examined from a strictly ecological or technological perspective, but rather within the context of its broader cultural-ecological system.

Introduction

The Oldowan is relatively simplistic as it consists primarily of core and flake tools (Leakey 1971). In contrast to earlier typological approaches, experimental models by (Toth 1985) suggest that the Oldowan is a simple core and flake industry whose primary goal is the removal of flakes with sharp cutting edges. In spite of its superficial simplicity, Oldowan stone tool variation is a vast resource of information regarding Early Pleistocene hominin behavior. Technological analyses show that Oldowan hominins had at least a basic understanding of the general principles of flaking and selection of suitable tool stones for artifact manufacture (Braun et al. 2019; D. R. Braun, Plummer, Ferraro, et al. 2009; Delagnes and Roche 2005; de la Torre 2004; Roche et al. 1999; Semaw 2000; Stout et al. 2005). In addition, Oldowan hominins also transported stone tools various distance to the places where they are used and discarded (Blumenschine and Peters 1998; D. R. Braun, Ditchfield, et al. 2008; Harmand 2009; Hay 1976; Isaac 1984; Potts 1991; Toth 1985). Despite early suggestions that the Oldowan was a largely expedient tool kit (Chavaillon 1970), it may reflect a more nuanced technical system, where raw material is acquired, transported, utilized, maintained and eventually discarded (Isaac 1984).

A major difficulty in the study of Oldowan hominin behavior is linking variation in artifacts to individual influences on behavior (Gallotti 2018; Roche, Blumenschine, and Shea 2009). While socio-cognitive approaches only require examining technological strategies present in the artifacts themselves, ecological analyses require integrated ecological and functional data sets. Demonstrating the influence of ecological parameters on stone tool use requires establishing spatial relationships between measures of stone tool utilization and landscape features such as raw material sources and paleogeographic settings (Blumenschine and Peters 1998; Blumenschine et al. 2008; Blumenschine, Stanistreet, and Masao

2012; @ D. R. Braun, Rogers, et al. 2008; D. R. Braun, Plummer, Ditchfield, et al. 2009; Isaac and Isaac 1997; Rogers 1997). While previous work on this topic has demonstrated the influence of raw material access on Oldowan assemblages (Blumenschine et al. 2008), little work has been done demonstrating its direct influence on technological variation in the Oldowan. The site of Kanjera South provides an opportunity to do so. Extensive research on the technological context has characterized not only the technological strategies employed by hominins, at this site, but also the landscape context of the site (Behrensmeyer et al. 1995; D. R. Braun, Ditchfield, et al. 2008; D. R. Braun, Plummer, Ditchfield, et al. 2009; D. R. Braun, Plummer, Ferraro, et al. 2009; Ditchfield et al. 2018; Bishop et al. 2006; Kent 1942; Lemorini et al. 2014, 2019; Oliver et al. 2019; Plummer, Bishop, et al. 2009; Plummer et al. 2001, 1999; Plummer and Bishop 2016). Here we present an integrated approach that examines Oldowan lithic technology from an ecological context. The results of this study contribute to the exploration of ecological and socio-cultural influences on Oldowan artifact variation.

Background

Given the dynamic system that Oldowan tools ultimately reflect, it is argued that stone tool variation is influenced by function, ecology, culture and cognition (Gallotti 2018; Isaac 1984; Plummer, Bishop, et al. 2009; Toth and Schick 2006) (Figure 1). Understanding the role of function in shaping Oldowan stone tool variation is constrained. The uses of Oldowan tools beyond evidence of cutting, and flake production is not well known. A small number of use-wear studies are beginning to shed light on the diversity of functions that Oldowan flakes were used for (Keeley and Toth 1981; Lemorini et al. 2014, 2019). The impact of these functions on Oldowan stone tool variation remains unclear. As a

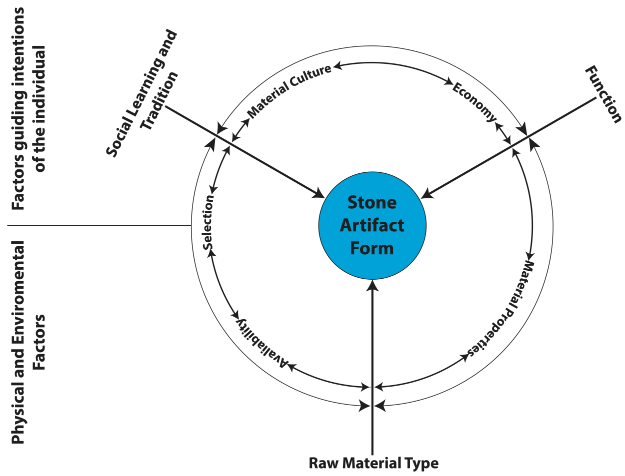

Figure 1: A diagram of factors that contribute to stone tool variation. Adopted from Isaac (1984).

result, Oldowan studies have focused primarily on drawing behavioral inferences from explorations of hominin ecology, culture and cognition derived from the morphological variation in stone tools. However, these various aspects of hominin life-ways are seldom studied in tandem.

The ecological approach views tools as an extra-somatic mechanism for solving environmental problems (Binford 2001). This approach was originally championed by the work of Glynn Isaac, John Desmond Clark, and their students (Clark 1975; Harris 1978; Isaac and Isaac 1997; Shick 1987; Toth 1987, 1982). In this perspective technology is considered to be a dynamic process that is adapted to the temporal and spatial distribution of resources (Bamforth 1990; Isaac and Harris 1976; Isaac 1981; Ludwig and Harris 1998; Nelson 1991; Peters and Blumenschine 1995; Rogers, Harris, and Feibel 1994; Toth 1985). In essence this approach investigates artifacts as dynamic objects that are a part of the hominin foraging system. One component of this approach is the concept that artifacts reflect movement of stone resources across landscapes often referred to as the "the flow of stone" model (Isaac 1984). Some artifacts are produced and discarded whereas others are transported away from the site. Understanding how this flow of stone through structured landscapes produces inter-site assemblage variability provides insight into the ecology and foraging strategies of early hominins (Blumenschine, Stanistreet, and Masao 2012). As a result, a variety of models have been proposed and debated for how assemblage composition, lithic attributes and artifact density reflect land-use patterns at multiple spatial scales (Binford 1976; Foley 1981a, 1981b; Isaac 1983, 1981; Isaac and Harris 1976; Shick 1987; Toth 1987). Ecologically oriented research often measures aspects of stone tool variation in relation to measures of tool utilization and transport. Quantitative or ordinal variables such as mass, length, proportion of cortex, and flake scar density are often compared alongside landscape variables such as distance to raw material source and paleogeographic context (Andrefsky 2009, 2008; Blumenschine, Stanistreet, and Masao 2012; Bunn et al. 1980; Davies, Holdaway, and Fanning 2018; Douglass 2010; Holdaway, Stern, and Chauhan 2004; Brantingham 1998; Kuhn, Raichlen, and Clark 2016; Toth 1987). Examples of this type of approach includes studies of artifact variation throughout the Okote Member of the Koobi Fora Formation. Paleogeographic context appears to influence the transport patterns and reduction intensity of these artifacts when they are discarded (@ D. R. Braun, Rogers, et al. 2008; Rogers, Harris, and Feibel 1994; Rogers 1997; Stern, Porch, and Mcdougall 2002). At Olduvai, quartz artifacts vary in size and abundance according to their distance from a large outcrop of quartz called Naibor Soit (Blumenschine et al. 2008).Measures of cortex and core reduction have shed light on the dynamic input-output system under which Oldowan lithic assemblages form (Bunn et al. 1980; Rogers 1997;

Toth 1987; @ D. R. Braun, Rogers, et al. 2008).

An alternative approach to the ecological focus, is one where the actions and thoughts associated with stone tool production are highlighted (Sellet 1993). This is sometimes referred to as the technological approach (Soressi and Geneste 2011). From this perspective, the variation seen in all technology stems from socially mediated images and thoughts (Inizan et al. 1999). The various combinations of ways to flake, shape or retouch stone are argued to reflect the different knapping strategies that characterize the skills of a group or individual (Delagnes and Roche 2005). From this perspective stone tools reflect the cognitive capacity and the technical competence of Oldowan tool makers (Roche, Blumenschine, and Shea 2009; Schick and Toth 1994; Stout et al. 2015; Stout and Chaminade 2009; Toth and Schick 2018). In particular, certain components of the artifact production process (e.g. complex series of nested goals) appear to require specific cognitive traits (Wynn and Coolidge 2016). Oldowan variation is interpreted as differences in skills, cultural traditions, or even different taxa (Delagnes and Roche 2005; Roche et al. 1999, 2018; Roche, Blumenschine, and Shea 2009; Stout et al. 2010). Technological analyses have been instrumental in revealing the rules that govern stone artifacts production. Analysis of lithic assemblages from West Turkana in Kenya show that hominins had already mastered flake removal and how to maintain and exploit pre-existing platforms (Delagnes and Roche 2005).

Moreover, differences in the arrangement of flake scars, refit sequences, the frequency of knapping accidents are used to infer different production strategies from Oldowan lithic assemblages. Differences in the inferred skill of toolmakers at Lokalelei 1 and 2c are so striking that the author suggested that the differences arise from 2 different social groups or possibly different species of hominins (Delagnes and Roche 2005). At Gona, differences in the proportion of reduction strategies between sites have been argued to reflect cultural traditions of specific groups (Stout et al. 2010, 2019). At a broader scale, some researchers have argued that the variation in the Oldowan is similar to the regional variation in the observed in chimpanzee cultures (Barham and Mitchell 2008; Whiten et al. 1999; Whiten, Schick, and Toth 2009). The social context within this variation is interpreted to reflect potentially different social learning mechanisms in the archaeological record (Morgan et al. 2015; Stout et al. 2019).

The vast majority of research on Oldowan artifacts can be identified as falling into one the previously described categories (i.e. either ecologically focused or socially mediated). The singular focus of most Oldowan research on either ecological or technological questions has an impact on the current status of Oldowan research. The manner in which the Oldowan is described, and the methods used to describe it, depend heavily on the theoretical position of the analyst (la de Torre and Mora 2009). In a way, this is problematic because as figure 1 demonstrates, the factors that contribute to stone tool variability are not mutually exclusive and likely interact with one another For example, the strategy used to reduce a core will affect the proportion of different Toth types produced (Stout et al. 2019, 2010). This will also likely influence how cortex is distributed across a landscape (Toth 1987). Therefore in the absence of a more integrated approach, differences in the representation of flake types (i.e. Toth Types) between two sites could be interpreted as varied foraging techniques when in reality they result from different tool reduction strategies (or possibly a combination of both). Therefore, in this example, reduction strategy and measurements of cortex must both be considered before discussing the aspects of behavior reflected in a given assemblage. In other words, without considering the broader ecological context of the Oldowan it may be impossible to disentangle technical competence of Oldowan knapppers from technological variability (or *vice versa*).

Distance - decay relationships between the location of tool-stone sources and stone tool discard is prevalent in Oldowan assemblages (Blumenschine et al. 2008; @ D. R. Braun, Rogers, et al. 2008; Toth 1985). However, these patterns are often described in terms of reduction intensity, size of flakes and cores, or the representation of cortex. Oldowan cores that are more reduced often involve greater levels of core rotation (Toth 1982). It is possible that differences in technological strategies may sometimes arise due to raw material abundance. Moreover, it may be that Oldowan stone tool variation may be the result of a complex interaction between social mechanisms of information transfer and ecological context. Understanding the significance of Oldowan variability requires an integrated approach which considers the context of tool use as well as the context of availability of resources. The assemblage of Oldowan artifacts from Kanjera South provide the opportunity to understand an artifact record within the context of raw material availability and technological variability (Plummer and Bishop 2016).

Background to Kanjera South

The site of Kanjera South is situated on the northern side of the Homa Peninsula on the edges of the Nyanza Rift near the shores of Lake Victoria (Plummer, Ditchfield, et al. 2009; Plummer et al. 1999). The archaeological site is in an amphitheater of sediment that has been exposed by the Kanjera River that is draining off the Homa Mountain carbonatite complex (figure: \ref{map}). This volcanic edifice dominates the sedimentary processes and basement geology of the region (LeBas 1970). The site of Kanjera South was excavated from a 3 meter stacked sequence of clays and silts that record extensive hominin behavior in the form of stone artifacts and bones with surface modifications that are

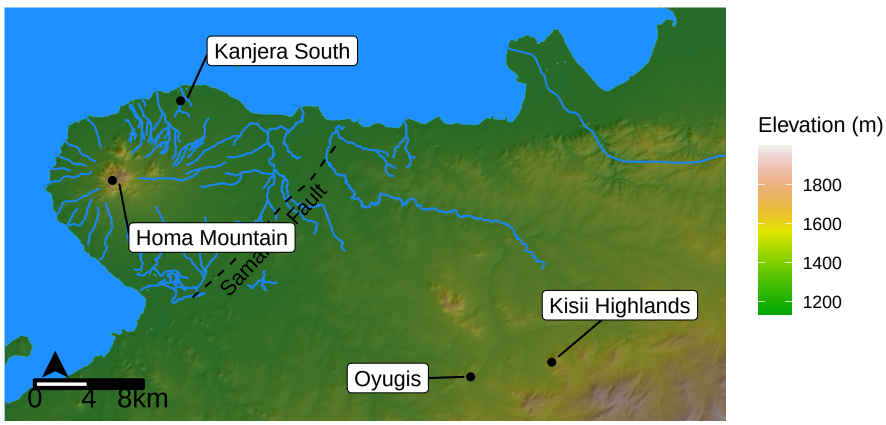

Figure 2: A map of the Homa Peninsula. Kanjera South is situated to the East of Homa Mountain. The Homa Mountain carbonatite center is the primary source of the local raw materials including Homa limestone (HLi), Homa Phonolite (HPh), and Fenetized nyanzian rocks (FNy). Distant or exotic raw materials originate much farther to the east but they can be found in drainages east of the Samanga Fault. These include Bukoban andesite (BBa), Bukoban felsite (BFe), Bukoban quartzite (BQu), Nyanzian rhyolite (NyR), and Oygus granite (OGr)

indicative of the butchery of meat and acquisition of marrow (D. R. Braun, Plummer, Ditchfield, et al. 2009; Plummer, Ditchfield, et al. 2009). Extensive excavation has recovered over 3000 fossils and similar numbers of stone artifacts (Plummer, Bishop, et al. 2009). The stratigraphy at Kanjera South is made up of approximately 30 m of fluvial, colluvial and lacustrine sediments (Ditchfield et al. 2018). This stratigraphic sequence is well dated to ~2. Ma using a combination of paleomagnetic and biochronological markers. These sediments are formally assigned to the Southern Member of the Kanjera Fm (Behrensmeyer et al. 1995; Plummer et al. 1999). There are five beds at Kanjera South (from oldest to youngest KS-1 to KS-5) with artifacts and fossils concentrated in the sands and silts of upper KS-1 to KS-3 (Ditchfield et al. 2018). Lithics and fossils are thought to have been predominantly accumulated by hominins except for those found within thin, discontinuous conglomerates which represent brief intervals of higher energy water flow (Ditchfield et al. 2018; Ferraro et al. 2013).

The lithic assemblage recovered from exacavations at Kanjera South represents one of the largest single accumulations of Oldowan artifacts in association with modified fossil bone (Plummer 2004). The largest site (169 m^2) yielding the bulk of the archaeological finds was Excavation 1. The frequencies of different bovids in these beds indicates that the Kanjera South landscape, unlike the setting of most of the Oldowan sites, was dominated by a grasslands as opposed to trees (Plummer, Ditchfield, et al. 2009). This is further supported by the stable isotope analysis of pedogenic carbonates and tooth enamel indicating a relatively high proportion of plants that use a C4 photosynthetic pathway. The fossils associated with the stone artifacts at Kanjera South exhibit substantial evidence of hominin involvement in the accumulation of materials (Ferraro et al. 2013). Evidence from bone surface modifications as well as the proportions of bones modified are similar to patterns seen in “hominin first” experimental

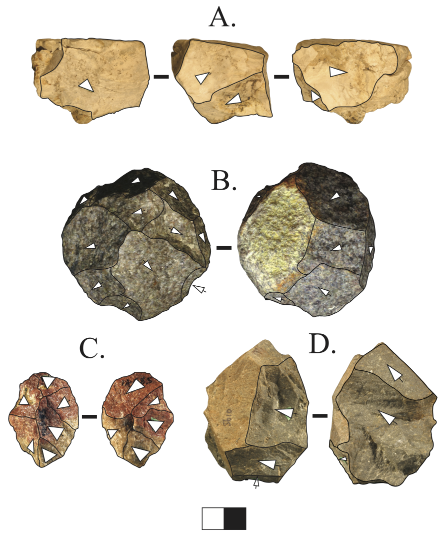

Figure 3: Examples of the found at Kanjera South. (A) Core produced on Homa limestone. (B) Core produced on Oyugis granite. (C) Core produced on Bukoban quartzite. (D) Core produced on Fenetized nyanzian.

datasets for small mammals, while larger mammals show more mixed access (Ferraro et al. 2013). The totality of the zooarchaeological evidence at Kanjera strongly implicates a scenario where hominins had early access to small carcasses. Evidence from mortality profile data also supports the inference that hominins may have been able to access smaller carcasses prior to carnivores and that larger carcasses were at times scavenged (Oliver et al. 2019).

The stone artifacts from Kanjera South reflect a wide diversity of technological adaptations (D. R. Braun, Plummer, Ditchfield, et al. 2009). The high diversity of the local geology on the Homa Peninsula provided a wide choice of different raw material types that hominins could incorporate into their toolkit . There are 16 formally described raw material types with many additional types that only appear in small quantities within the assemblage (D. R. Braun, Plummer, Ditchfield, et al. 2009). A detailed provenance study of the rock types used to make stone artifacts at Kanjera documented two features that distinguish the Kanjera South assemblage from many other Oldowan assemblages. The first is the presence of transport to Kanjera South from conglomerates that are at least 10 km away from the site (D. R. Braun, Ditchfield, et al. 2008). The second is the systematic selection of rocks that have specific mechanical properties (D. R. Braun, Plummer, Ferraro, et al. 2009). Hominins selected rocks that fracture consistently and also had edges that resisted wear. The selection of certain rock types exceeds that which is seen in other Oldowan assemblages. Furthermore the intensity of selective behaviors seems to parallel rock properties. These differences in rock properties are reflected in the flaking technology (figure 3). Unidirectional and multidirectional flaking patterns feature prominently in this assemblage. However, the flaking patterns track raw materials differences and there appears to be a concerted effort to extend the use life of cores in some raw materials by increasing the length of flaking sequences in some raw materials. These different technological strategies applied to different raw materials results in a high diversity of core reduction strategies in the Kanjera South Assemblage (D. R. Braun, Plummer, Ditchfield, et al. 2009).

In addition to information regarding the transport and selection of certain raw materials, detailed studies of the micro-wear on the stone artifacts from Kanjera provide insights into artifact use (Lemorini et al. 2014, 2019). Usewear evidence suggests that the tool used by hominin at Kanjera were used for a variety of different activities. Most of these actions involve cutting, and the different raw materials appear to be used on different substrates. Usewear studies also suggests that some of the stone tools were used for modifying wood. This suggests that hominins were using stone artifacts to fashion other wooden tools (Lemorini et al. 2019). Combined with the transport information, the sum of the information about stone artifacts at Kanjera South suggests that stone artifacts represented a significant component of the extractive foraging adaptation of Oldowan hominins.

Methods

Oldowan tools undergo a series of transformations, through the removal of flakes, from the time they are acquired until they are ultimately discarded (Andrefsky 2009). As reviewed above, the flake removal process relates to a diversity of social and economic factors surrounding tool use and production. Here we explore the interaction of these factors on stone tool variability. As such, this study combines the pre-existing knowledge of stone tool production regarding, raw material properties, provenience and technology at Kanjera South with newly applied measures of stone tool utilization. This provides a novel means to understand Oldowan stone tool production from a multifaceted point of view in which the relationships between stone tool utilization, landscape-scale raw material constraints, and stone tool production strategies can be investigated.

Table 1: A list of rock types included in this analysis

Raw.Material	Abreviation	Origin	Provenance
Fenetized nyanzian	FNy	Homa Mountain	Local
Homa limestone	HLi	Homa Mountain	Local
Homa phonolite	HPh	Homa Mountain	Local
Bukoban andesite	BBa	East of Samanga Fault	Exotic
Bukoban felsite	BFe	East of Samanga Fault	Exotic
Bukoban quartzite	BQu	East of Samanga Fault	Exotic
Nyanzian rhyolite	NyR	East of Samanga Fault	Exotic
Oygus granite	OGr	Oygus	Exotic

We characterize the technology of stone tools produced on both distant and local materials at Kanjera South (Table 1) through the study of the core and complete flake assemblages (i.e. our analysis at this time does not incorporate angular fragments). Tool utilization for cores was measured in terms of reduction intensity. We estimate the proportion of mass lost prior to its discard following the methods outlined in (Douglass et al. 2017). In addition, tool utilization is also examined by estimating the relative proportion of flakes in the Kanjera South assemblage that derive from early or later parts of the reduction sequence. We identify the sequence order that flakes were removed from their cores by using previously published models that use quantitative measures of flakes to predict their placement in a reduction sequence (D. R. Braun, Tactikos, et al. 2008). Flake sequence refers to the order that flake was removed from the core. Flake sequence data provides an independent measure of tool utilization that could be compared to the estimates of core reduction. Additionally, it also provides a way to examine the amount of flake production that occurred at Kanjera South. If cores were transported directly to Kanjera South and reduced, then the early flake sequences (i.e. the first flakes off the core) would be present in the assemblage. However, if early stage flakes are not present in the assemblage then it can be inferred that cores were utilized elsewhere prior to their transport to and discard at Kanjera South. Measures of core reduction intensity are analyzed along-side technological strategies (e.g. bidirectional) utilized in core reduction. Furthermore, core reduction and flake sequence values can also be examined according to raw material type. This provides a means to examine the impact of raw material properties and provenience on core reduction and technology. The integration of these multiple lines of evidence allows us to place stone tool variability at Kanjera south within the broader technological system in which it took place.

Characterizing Stone Tool Utilization.

Tool utilization has been extensively researched in lithic analysis (see Andfresky 2009 for overview). Most studies of tool utilization focus on the degree of artifact reduction as a proxy for the use-life of an artifact (although these things are related but they are not the same; Shott (1996)). Reduction intensity can be calculated for a variety of artifact types (Dibble 1995). Currently several methods exist for estimating the extent of core reduction. The majority of these methods rely on establishing linear relationships between core attributes and the amount of mass lost during artifact production to predict mass removed from a core (Clarkson 2013; Douglass et al. 2017). This study uses the methods outlined in Douglass et al. (2017) to estimate core reduction intensity as the proportion of mass lost.The predictive model developed by Douglass et al. (2017) incorporates a series of core attributes beyond simply surface area and total number of flake scars. This model considers, the number of flake scars, exploitation surfaces, the number of exploitation surface convergences, the proportion of cortex, and average platform angle to estimate core reduction intensity.

The *number of flake scars* intuitively refers to the number of previous flake removals present on the core. The *number of exploitation surfaces* refers to the number of areas of the core where flakes were removed along a similar axis. This variable is related to core rotation which is argued to increase as core reduction increases (e.g. Delagnes and Roche 2005). The *number of exploitation surface convergences* documents the number of times different exploitation surfaces intersect with each other. Throughout reduction exploitation surfaces with different flaking axes tend to converge (Braun 2005, Douglass et al 2017). The proportion of cortex has an intuitive relationship with core reduction intensity. That is, the total proportion of the core that possesses cortical surface area will diminish during reduction. *Average platform angle*, measured in degrees, refers to the mean angle between striking surfaces. Various experimental replication studies show that, as this angle approaches 90°, it becomes increasingly difficult to detach a flake (Cotterell, Kamminga, and Dickson 1985). Therefore, as a core approaches exhaustion, the platform angles on the core are likely to approach 90° (Douglass et al. 2017). Specifically, the method by Douglass et al. (2017) utilizes a generalized linear mixed model to examine the effects of predictor variables on core reduction intensity and ultimately predict the percentage of mass lost from a core. The added benefit of this model is that it is directly applicable to the materials analyzed in here, as it is was developed in validated on experimental material and a subset of archaeological material from Kanjera South (D. R. Braun, Tactikos, et al. 2008). These details are discussed in Douglass et al. (2017).

Flake Sequence Estimates

Flake sequence is a common analytical method in American archaeology (Andrefsky 2009; Bamforth 1986) but is also applied to Early Stone Age assemblages in various forms (D. R. Braun, Tactikos, et al. 2008; de la Torre Ignacio 2011; Stout et al. 2010; Toth 1985). In the Early Stone Age, flake sequences are most commonly characterized using Toth types, which classifies flakes into six different stages depending on the presence of cortex on a flake's platform and dorsal surface (Toth 1985). Here we follow D. R. Braun, Tactikos, et al. (2008), using a multi-linear model to estimate flake sequence values. This methodology is specifically focused on understanding the approximate location of a flake within a reduction sequence. Unlike Toth's flake types, which is focused on relative sequence information, the multi-linear model allows for an absolute placement of a flake within a reduction set (within a prescribed error). The multiple linear regression uses flake length, width, number of platform facets, number of flake scars, and the number of flake scar directions; specific details for each measurement are clearly outlined in D. R. Braun, Tactikos, et al. (2008) (page 2156, figure 3). Before the sequence number can be estimated, the number of flake scars and amount of dorsal cortex must be divided by the log of the surface area of the flake (D. R. Braun, Tactikos, et al. 2008). These variables are then used by the predictive model to estimate the flake sequence number. Flake sequence estimates have a maximum error between +/- 8 sequences. However, an application of the method to refitting sequences from the Koobi Fora formation showed it always places flakes in their relative order(D. R. Braun, Tactikos, et al. 2008). Therefore, while information derived from individual flake sequence estimates may be coarse-grained, it remains useful for assemblage scale comparisons.

Edge to mass ratios

Measurements of tool use are often associated with enumerating the details of the reduction of artifacts (Dibble 1995; Eren and Sampson 2009). This is largely because of the reductive nature of stone technology (i.e. the process of producing stone tools always produces a smaller byproduct). However, some have also reviewed the general efficiency of this flaking process (Braun and Harris 2003; Brantingham and Kuhn 2001; Eren, Greenspan, and Sampson 2008; Muller and Clarkson 2016). Unfortunately, the study of efficiency in artifact production is not well standardized. There are some studies that investigate the overall efficiency of specific knapping strategies (Brantingham and Kuhn 2001; Eren et al. 2008). Others review efficiency as it pertains to individual flaking events within an overall technological framework (Braun and Harris 2003). Identifying the mechanisms that result in highly efficient tool forms is not well understood (Lin et al. 2013; Dogandžić, Braun, and McPherron 2015). Yet it is clear that there is variation in how efficient some technologies are (even though the metric for identifying efficiency is debated; Eren et al. 2008). Assuming that most stone tools are produced to create sharp edges, one possible measure is estimating the amount of sharp edge produced per given unit of mass. Technologies that produced a higher amount of edge per volume of material can be considered more efficient (Braun and Harris 2003). Here we use a measure of edge that is based on tracing the edge of whole flakes (Braun and Harris 2003; Isaac and Isaac 1997). To calculate efficiency this edge estimate is divided by the logarithmic transformation of mass. The reason for this transformation is that mass increases in three dimensions (i.e. volumetrically) and the edge of a flake increases in two dimensions. The logarithmic transformation of mass prevents distortions of this ratio that are the result of general size parameters. For example, very small flakes have relatively high edge for a given amount of mass, but this is not always the most efficient way to produce the greatest amount of edge relative to volume (e.g. see discussions on this topic in Kuhn 1991). Flakes that have high amounts of edged relative to their mass tend to be relatively thin flakes, and there is the possibility that the efficiency of these tools is limited by their capabilities to complete certain tasks (e.g. tacks that require intensive use of edges such as hide scraping may not be feasible with relatively thin flakes). Here we calculate the edge to mass ratio of flakes within raw material categories. We then aggregate this measure across raw materials types to assess the overall efficiency of a given raw material. These aggregate measures are likely more reflective of the generalized pattern of efficiency in tool production over time at the Kanjera South locality.

Results

Core Utilization

Core reduction intensity estimates reveal that there is a wide range of variation in the amount of mass that was removed from the cores at Kanjera South. Some

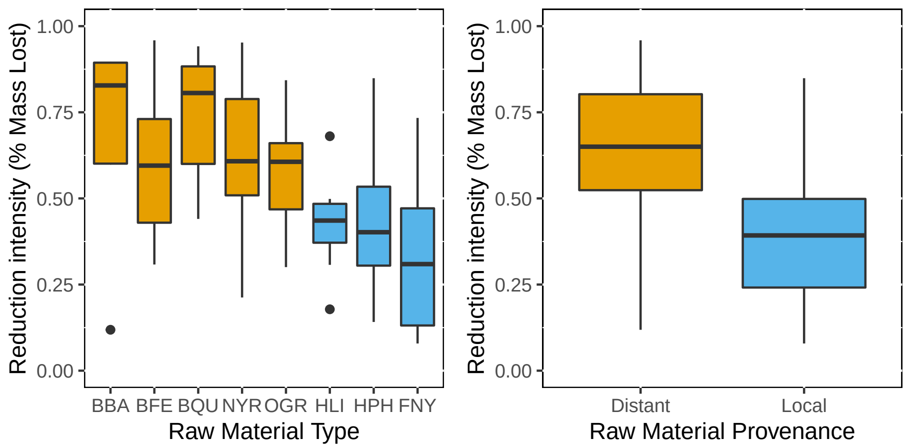

Figure 4: The distribution of core reduction intensity values as predicted by the GLMM (Douglass et al 2017). The results show stark differences in the degree of reduction in materials originating from more distant sources than those that originate from local sources of stone.

cores were minimally utilized whereas others were reduced as much as 95% of their original mass. There is also a significant relationship between core reduction intensity and raw material type (Kruskal-Wallis, p = $<$ .0001). This pattern appears to be driven by raw material provenance. Cores produced on raw material types that originate from more distant sources (BBa, BFe, BQu, NyR, and OGr) are on average more substantially reduced than those that occur locally (FNy, HPh, HLi) (Kruskal-Wallis, $p < .001$, Figure: 4).

The application of the flake sequence model to the Kanjera South assemblage reveals a similar pattern to that found in the core reduction intensity analysis. Flake sequence values range from the first flakes off the core to the 30th flake in the sequence. As with core reduction intensity, raw material type has a significant influence on flake sequence values (Kruskal-Wallis, $p< .001$). The largest differences are, again, those between rock types derived from more distant sources and those found locally. Flakes produced on rock types from more distant raw material sources are from later in the reduction sequence (figure 5), while flakes from the locally found materials are from earlier stages of reduction 5.

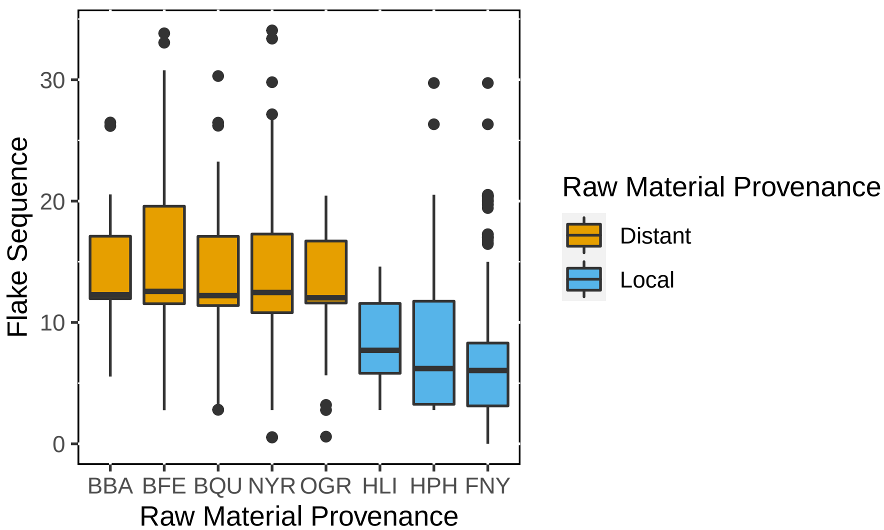

Figure 5: The distribution of flake sequence values present within the Kanjera South flake assemblage. The primary differences in flake sequence values are between materials originating from more distant sources than those that originate from local sources of stone.

Interestingly, there is a striking amount of homogeneity in the distribution of flake sequence values associated with exotic or distant raw materials. Aside from Bukoban Felsite (BFe) the inter-quartile range of flake sequence values are very similar from distant sources. Even though Bukoban Felsite has a wider range than the others, its median is nearly the same as the others. The flake sequence values associated with flakes from the local materials are also similar to each other but show slightly more variation. Homa Phonolite exhibits the widest range of flake sequence values.

As previously reported (D. R. Braun, Plummer, Ditchfield, et al. 2009), the Kanjera core assemblage is comprised of a wide variety of technological types or core reduction strategies. The frequency of core reduction strategies present shows a significant relationship with the raw material type (Fishers exact test, p-value: $< .001$). In general, raw materials that derive from more distant sources, are represented by core reduction strategies that involve a greater number of core rotations or more complex rotations (i.e. centripetal flaking, figure: 6). Though unifacial and unidirectional reduction strategies are present in small frequencies, there is a greater representation of centripetal, bifacial and multifacial exploitation strategies in materials from more distant origins (Figure: 6). On the other hand, local materials such as the Fenetized Nyanzian (FNy) and Homa Phonolite (HPh) are represented by greater number of unifacial or uni-directional core reduction strategies (Figure: 6). Homa Limestone, runs contrary to this general pattern. Although Homa Limestone is found in abundance locally, cores produced on this raw material type are often multi-facially reduced. However, as is addressed in the discussion this is likely related to the properties of the raw material itself (D. R. Braun, Plummer, Ditchfield, et al. 2009). When core reduction intensity is compared according by core reduction strategy an interesting pattern emerges. Unifacial and unipolar, core reduction strategies result in less reduction than strategies that require bifacial, multifacial or polyhedral strategies (Kruskal Wallis, P-value: $< .001$) (Figure: 6). In other words, core reduction strategies that require fewer core rotations, such as unifacial and unidirectional strategies, are less reduced than those that involve more complex rotation strategies.

Flake efficiency

Analysis of the relative proportion of edge to mass in flakes indicates significantly different technological strategies applied to the different raw materials from the Kanjera South assemblage. Although the mean values of the different raw materials are relatively similar, the overall distribution of values indicates that rock types from sources that are further away from Kanjera South (e.g. rhyolite, felsite, quartzite) are produced in a way that allows for much higher efficiency values than those seen in the rock types found close to Kanjera South. In particular, the relatively low values seen in the Fenetized Nyanzian and Homa

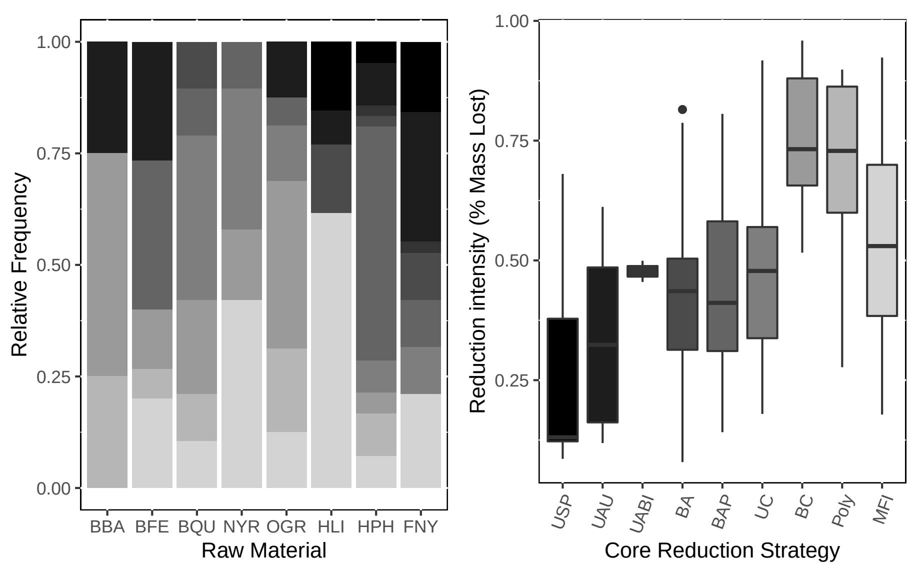

Figure 6: The distribution of core reduction strategies by raw material type. With the exception of Homa Limestone, raw materials that derive from the Kisi highlights more greatly represented by complex core reduction strategies than those that can be found in the immediate vicinity of Kanjera South. **USP**: Unifacial Simple Partial. **UAU**: Unidirectional abrupt unifacial. **UABI**: Unifacial abrupt bidirectional. **BA**: Bidirectional Abrupt. **BAP** Bifacial Partial. **UC**: Unifacial centripetal. **BC**: Bifacial Centripetal. **Poly**: Polyhedral. **MFI**: Mutifacial Irregular.

limestone indicate that flakes made on these rock types were produced in a manner that does not increase the use life of these cores (@ D. R. Braun, Rogers, et al. 2008; Shott 1996; Shott and Sillitoe 2004). In particular the differences between the rocks types from the Kisii highlands (Bukoban quartzite, felsite and basalt) show signficant differences from those rock types that can be found in the drainages near Kanjera (e.g. Homa Limestone and Fenetized Nyanzian, $p<.01$ for all pairwise comparisons between Homa Limestone and all Bukoban rock types; $p<.001$ for all comparisons between Fenetized Nyanzian and all other rock types Kruskal-Wallis Rank Sum test, chi2=312.70, df=5, pairwise comparisons between raw materials use Dunnn's Test with Benjamin-Hochberg correction for multiple comparisons). It should be noted that even though there are significant differences between the edge to mass ratios, the distributions show significant overlap (Figure \ref{flake_efficiency}. This indicates that while it is physically possible to produce flakes with similar edge to mass ratios in each raw material type, hominins at Kanjera South did not implement this strategy as frequently on raw materials that were locally abundant. Hominins at Kanjera South consistently produced flakes with greater edge and less mass from rock types that came from more distant sources. We only include rock types that have greater than 50 flakes because the wide variance in values seen in this measure results in wilidly divergent values in small samples.

Discussion

The Influence of Raw Material Properties

The results of this study show an interaction between stone tool utilization, raw material type and core reduction strategies. The most striking distinction is the difference in the degree of utilization of materials from local and distant sources. That is, cores that are derived from the drainages of the more distant

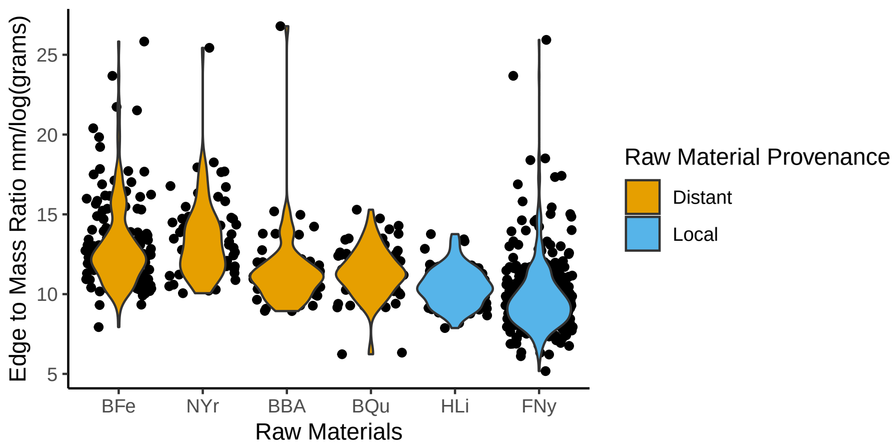

Figure 7: Boxplots of the measures of flake efficiency. Y-axis represents perimeter of flakes divided by a logarithmically transformed mass value.

Kisi highlands are significantly more reduced than those from local sources. This is also reflected in the flake sequence data. Within the Kanjera South flake assemblage, those produced on exotic raw materials are more likely to be from later in the reduction sequence than flakes from locally sourced materials (Figure 5). This difference can be explained by a few different factors. Firstly, raw material properties play a role in causing these differences. The local fenetized rocks (FNy) are often discarded before complete reduction because of the intersection of removals with step fractures or preexisting internal fracture planes present in the highly metasomatized rocks (D. R. Braun, Plummer, Ferraro, et al. 2009). The chalky nature and block-like geometry of Homa limestone (HLi) also limits the number of flakes that can be removed. In contrast, the majority of raw materials from more distant sources possess fewer flaws and fracture more predictably than those found locally (D. R. Braun, Plummer, Ferraro, et al. 2009).

However, differences in material properties do not explain all of the differences in reduction intensity between local and exotic materials. If all of the cores that were discarded due to presence of internal flaws are removed from the assemblage (figure 6), the overall pattern remains. In addition, Homa phonolite, a local raw material, does not have the defects common in other local raw materials but it is still less reduced than the nonlocal raw materials. In contrast with the other exotic materials, the properties of the Oyugis granite (OGr) also constrains the removal of flakes. The particularly coarse grained nature of this rock type alters its fracture pattern. It is difficult to maintain angles of less than 90 degrees. It is likely that hominins could only exploit pre-existing angles on these granite blocks, thus limiting the degree that they could be reduced (D. R. Braun, Plummer, Ditchfield, et al. 2009). Despite the limitations imposed by its material properties, Oyugis granite is still more reduced than any of the local raw materials (figure 4). Previous research shows that the exotic raw materials that were transported to Kanjera South not only fracture more predictably but also produce flakes with more durable edges (D. R. Braun, Plummer, Ferraro, et al. 2009; de la Torre 2004; Ludwig and Harris 1998). The need to reduce relatively lower quality material may be related to the durability and the efficiency of the produced edges. In other words, flakes produced on local rock types have shorter use-lives because their edges dull more quickly. The consequence of this, is that for any given use, more flakes of a local raw material are required. In this sense, the high abundance of these materials and the relatively quick dulling of their cutting edges may explain the high frequency of local raw materials in the Kanjera South assemblage.

Implications for Land use

The stark differences in the degree of core utilization according to raw material origin also reflects a dynamic hominin land-use system. Flake sequence values associated with exotic materials are often from later in the sequence than those associated with local raw materials. This pattern could indicate that cores from exotic sources were often utilized prior to their arrival and discard at Kanjera South. The presence of highly reduced exotic materials in contrast with lightly reduced local materials may imply that hominins that visited the Homa Peninsula may have discarded more utilized exotic materials as they collected materials that were proximal to Kanjera as part of a mobile toolkit. This pattern has been observed at the site of FxJj 50 from the Okote Mbr. of the Koobi Fora Fm. (D. R. Braun, Harris, and Maina 2009). This may further suggest that stone tool acquisition and discard behavior may relate to the need to maximize the amount of utility hominins carried with them. **In this sense, hominins would have made decisions to discard raw material when opportunities to increase the amount useable volume was prssent.** The core reduction pattern at Kanjera South is also consistent with expectations of raw material procurement and utilization when conditions are neutral. Under neutral conditions, raw materials from more distant sources will be, on average, more reduced, than those from local sources (Brantingham 2003; Pop 2016). The fact that cores from more distant sources are more reduced than those from local sources is consistent with this pattern. This "distance-decay" pattern has been observed in numerous archaeological studies (eg. Blumenschine et al. (2008); Close (1999); Newman (1994); Toth (1985)). In addition, neutral expectations state that the variance in tool reduction intensity will decrease with distance from a given source. In other words, the variance in the amount of stone tool reduction intensity should be substantially lower in assemblages of tools from distant sources. The converse is also predicted by the distance-decay model. Variance in core reduction will be much greater in local sources.

This prediction of the distance-decay model is not supported by the Kanjera South data. In contrast, while exotic materials are reduced more more substantially than local materials, the interquartile ranges of flake sequence and core reduction measures of assemblages from distant sources are as wide (or wider) than those associated with local sources. This argues against a null hypothesis that the patterns seen in the lithic assemblage at Kanjera South formed under neutral conditions (i.e. no intentional attempt to increase the use life of artifacts from distant sources). It has been hypothesized that deviations from the neutral model of this nature may arise due to increasingly linear movements toward specific locations (Brantingham 2003; @ D. R. Braun, Rogers, et al. 2008). Moreover, subsequent work modeling the influence of directed movement towards attractors has shown that while a distance-decay pattern remains visible, tools from earlier stages of reduction will be over-represented (i.e. greater variance in reduction) (Reeves 2019). Thus, the greater than expected range in variance in the reduction intensity of distantly sourced cores may suggest that hominins directed their movement to Kanjera South.

The concept that hominins directed their movement toward Kanjera South, is supported by other archaeological and paleoecological evidence. Numerous taphonomic studies of the faunal assemblage from Kanjera South have verified that hominins efficiently exploited small bovids and may have processed larger carcasses that were scavenged from carnivores. (Ferraro et al. 2013; Oliver et al. 2019). Use-wear studies that demonstrate that hominins carried out a variety of resource processing activities with the stone artifacts that were produced at Kanjera South, including butchery and the processing of a variety of plants, including underground storage organs (USOs) (Lemorini et al. 2014, 2019). These studies attest to the resource rich environment in which Kanjera South was situated. These resources ultimately made the Kanjera South locale and the Homa Pennisula an attractive place for hominins, most likely for centuries given that the finds were made through three meters of sequence (upper KS-1 through KS-3). Thus, the patterns evinced by this study are the result of the repeated visitation by hominins over generations to Kanjera South, and these patterns likely reflect the broader foraging ecology of Oldowan Tool makers.

The interacting effect of land-use and material properties on lithic technology at Kanjera South.

The results of this study may also suggest that tool utilization, raw material properties and foraging ecology may interact in complex ways that structure the patterns of artifact variation we see at Oldowan sites. Kanjera South artifacts include a wide range of reduction strategies (D. R. Braun, Plummer, Ditchfield, et al. 2009; Plummer, Bishop, et al. 2009; Plummer et al. 2001; Plummer and Bishop 2016). These strategies have a similar appearance to the descriptions of tool forms that have been described in other Oldowan contexts (de la Torre and Mora 2005). Interestingly the different reduction strategies present at Kanjera South seem to be related to reduction intensity. Cores that are described as having bifacial, multifacial and/or centripetal patterns of removals exhibit high levels of reduction. Few of the unifacial cores and partial bifacial cores show this increased level of reduction intensity (Figure 6). It could be argued that this pattern is a consequence of the predictive model used to estimate core reduction intensity. The reduction intensity model predicts higher reduction intensity as core rotation increases. This is a pattern that has been identified in some experimental models of Oldowan core reduction (Douglass et al. 2017). However, this is not necessarily the case. Despite the fact that cores produced on Oyugis Granite and Homa Limestone are often irregular and multi-facial, the predictive model still discriminates between different levels of reduction in these cores. Complimentary support can be found in the flakes made from these raw materials. Flakes made from exotic cores exhibit flake sequence values that suggest they were produced from later in the flaking sequence. This independent line of evidence suggests that the predictive model of core reduction is not over estimated due to rotation. Rather, this model of reduction intensity is accurately identifying estimates of the length of core use life in these exotic cores. Therefore it is possible to examine the representation of various core reduction strategies in terms of raw material properties and land-use.

The representation of reduction strategies in each raw materials type also follows the interaction between raw material properties and broader land-use that is described above. Raw material properties have been shown to influence reduction intensity decisions previously (D. R. Braun, Plummer, Ditchfield, et al. 2009). The frequent application of unifacial reduction strategies to the locally obtained FNy may result from the limitations imposed by the internal flaws often present in the rock. In other words, hominins may have only been able to exploit a single surface on these metasomatized rocks before the knapping process encountered an internal flaw. Rather than attempt to overcome the flaw by rotating the core, the high abundance of FNy at KJS may have made it easier to simply discard the core and acquire a new nodule. High discard rates in contexts of abundant raw material has been observed in numerous archaeological and ethnographic contexts (Andrefsky 2008). Moreover, the technological analysis of the cores suggests that the high representation of irregular multi-facial cores produced in Homa Limestone (HLi) and Oyugis Granite (OGr) are the result of continuous core rotation to exploit naturally occurring angles (D. R. Braun, Plummer, Ditchfield, et al. 2009). The exploitation of naturally occurring angles in rocks is a fairly common feature of Oldowan hominins. (Delagnes and Roche 2005). Yet these mechanical issues do not explain all of the patterns seen at Kanjera South. Homa phonolite is one of the most homogeneous raw materials found at Kanjera South. Hominins at Kanjera South frequently implemented bifacial reduction strategy in these cores. It was possible to implement longer reduction chains in this material than was possible with the other local materials.

Yet the these cores are never reduced to the same degree as that seen in the exotic raw materials.

The cores produced on raw materials from the area surrounding Kanjera South (i.e. local materials) exhibit an even representation of various core reduction strategies. The same pattern is not seen in rocks transported over large distances. Exotic raw materials show a strong bias toward more reduced, complete bifacial and multifacial reduction strategies (Figure 6). While the HPh shows a high frequency of bifacial reduction, this reduction is only partial (Figure 6). Moreover, cores with multi-facial or centripetal flaking strategies are seldom produced on Homa Phonolite (Figure 6). This contrasts sharply with the prevalence of more intense core reduction strategies involving greater degrees of core rotation in rock types from further sources (e.g. Bukoban quartzite). This suggests that raw material properties is not the only factor influencing core reduction strategies.

The results of the edge-to-mass ratio data suggest that hominins applied a strategy that more efficiently produced flakes on rock types transported from greater distances from Kanjera South. In addition, previous research shows that exotic raw materials also produce more durable cutting edges (D. R. Braun, Plummer, Ferraro, et al. 2009). These two factors may have incentivized the retention of exotic raw materials within the hominin tool-kit. The stock of these "high quality" raw materials would have become increasingly more expensive (i.e. in time and energy) to rejuvenate as hominins moved away from the Kisi highlands (D. R. Braun, Ditchfield, et al. 2008). In this light, the high frequency of the bifacial and multifacial reduction strategies may have arisen from a need to maximize the amount utility that could be extracted from these cores. The exploitation of multiple flake removal surfaces on a core allows a core to remain active in a toolkit for a longer period of time. In later times hominins more frequently retouched formalized tools when the availability of raw materials becomes scarce (Clark and Barton 2017). In a similar sense, the application of complete bifacial and multifacial strategies may have allowed hominins to utilize these high quality exotic materials longer to optimize resource acquisition at Kanjera South.

It could be argued that this pattern reflects the high level planning and foresight required to utilize and transport tools within this dynamic system. However, simpler explanations should also be considered. Modeling work has shown that tools will inevitably become more utilized as they are transported from the source, even under neutral or random conditions (Brantingham 2003; Pop 2016; Reeves 2019). Experimental research has also shown that the wide range of formal types defined by Leakey (1971) could arise through a least effort flaking strategy (Toth 1985, 1982). More recently, Moore and Perston (2016) showed cores will eventually become bifacial or even multi-facial when the flaking procedure is systematically randomized. Thus, it may be possible to produce the differences in reduction intensity and reduction strategies observed between local and exotic materials by simply combining the influence of simple flaking procedures, stone tool transport, and raw material selection. Given the relationship between core reduction patterns and stone tool reduction intensity, the data from Kanjera South may suggest that different reduction strategies reflect different points on a reduction continuum rather than intentionally imposed strategies or socially mediated patterns of production. A similar notion has been proposed from LCT variability (Iovita and McPherron 2011). Oldowan researchers must consider the possibility that, in some cases, Oldowan core variability arises due to an interaction of simple flaking rules with broader ecological parameters. In this sense, some Oldowan core variation may be an emergent phenomenon, rather than a direct reflection of the intentions or information that was transmitted to the knapper.

Implications for the Oldowan as a whole.

The site of Kanjera South is unique in relation to Oldowan sites of a similar age or older. Many of the sites 2 million years old or older are situated in close proximity to raw materials sources and are comprised of a singular reduction strategy (Roche, Blumenschine, and Shea 2009; Plummer and Finestone 2018). In contrast, the assemblage at Kanjera South shows a substantial representation of exotic raw materials and a diversity of different core reduction strategies. The results from Kanjera South elucidate how the interaction of raw material properties, foraging ecology, and landscape scale constraints on raw material availability influence technological variability in the Oldowan. While many sites show strong selection for specific materials, the frequent use of unifacial reduction strategies at sites such as Lokalelei 2C, East Gona, Hadar, Omo, Ledi Geraru may relate to the overall abundance of knappable material that is immediately available at these site (Braun et al. 2019; Kimbel et al. 1996; Roche et al. 1999; Stout et al. 2005). In other words, there maybe little incentive to exhaustively reduce a core when material is so abundant (Clark and Barton 2017).

Kanjera South is also the only site from this time frame that is situated in an open grassland (Plummer, Ditchfield, et al. 2009). Humans tend to travel farther and more frequently in open arid environments than those that live in more productive environments (Burnside et al. 2012). Moreover savanna adapted Chimpanzees from Fongoli also possess a larger home range and practice fission-fusion less frequently (Pruetz and Bertolani 2009). If this was also the case for the hominins at Kanjera South, these factors may have required new technological strategies in order to accommodate expanded home range sizes. On a broader scale the technological diversity represented at Kanjera South may reflect adaptations to the specific contextual conditions at this locale. The stimulus for increasing the use lives of cores (through reduction intensity and efficient use of raw material) at Kanjera South may have been foraging activities that quickly dulled artifact edges (e.g., butchery and USO processing) (D. R. Braun, Ditchfield, et al. 2008; Lemorini et al. 2014) that were more frequently carried out in open habitats (Ferraro et al. 2013; Lemorini et al. 2019; Plummer, Bishop, et al. 2009).

Finally while the preceding analysis emphasizes the role of the broader environment and land-use on technological variability, ecology is not the sole driver of Oldowan technical variation. The inter-quartile ranges in figure 6 show a substantial amount of overlap between the reduction intensity and core reduction strategies. This suggests, that not all variation can be explained by environmental parameters such as raw material avalaibility and material properties. Moreover, inter-site differences between West Turkana sites are not easily explained factors such as raw material availability alone (Roche et al. 2018). This unexplained variation may be the result of socio-cultural dynamics that may have maintained information regarding the stone tool production process between groups. However, the fidelity and the mechanisms that underlie the maintenance of this information remain an open debate (Hovers 2012; Morgan et al. 2015; Stout et al. 2019; Tennie et al. 2017, 2016). However, the results of this analysis show that it may be counterproductive for research on Oldowan technology to focus on specific aspects of stone tool technology (Figure 1). Rather studies should examine the Oldowan within the broader socio-ecological system. It may be the interaction between function, ecology and sociality that provide information on the cultural capacity of Oldowan tool makers.

Conclusion

Despite the superficial simplicity of the Oldowan, its variability reflects a complex interconnection of ecological, behavioral and social factors. These factors are inextricably linked even though researchers often study them components in isolation. The lithic assemblage from Kanjera South provides an excellent opportunity to examine the interacting effects of raw material properties, provenance and availability of rock types and presumably social variation in the form of Oldowan artifacts. This is especially important given the context of other information we have from Kanjera that indicates that hominins butchered multiple small animals at this site and engaged in other subsistence strategies. Combination of quantitive measures of stone tool reduction with qualitative characterizations of lithic technology (e.g D. R. Braun, Plummer, Ditchfield, et al. (2009); Plummer and Bishop (2016)) provides new insights into the ecological factors that influence oldowan technology, and hominin behavior.

The fact that exotic materials are much more substantially reduced that from local sources reflects the differences in the quality of the raw materials available. The higher quality of the exotic materials would have incetivized the transport of these materials over longer distances. In this light, these differences in reduction also highlight that Oldowan tools were part of a mobile tool kit that reflects a broader land-use strategy. The marked differences in reduction intensity in combination with the paucity of early sequence flakes also suggests that exotic materials were often utilized prior to their arrival at Kanjera south. Although exotic materials are more reduced than local marerials the variance in the amount of stone tool reduction exhibited in the Kanjera South assemblage does not adhere to neutral expectations. This result suggests that the lithic assemblage at Kanjera South reflects a structured land-use pattern, that may indicate that hominins directed their movement, at least on occassion, to Kanjera South.

This pattern also appears to have an influence on the technological strategies employed by Oldowan tool makers at Kanjera South. The relationship between core reduction strategies and reduction intensity indicates that raw material quality and provenance have a strong influence on the technological variation observed within a lithic assemblage. While these results show that ecological parameters have a strong effect on stone tool variation, a substantial amount of variation remains unexplained by ecology alone. Overall, these results suggest that future studies must utilize a more integrated approach to understand the behavioral significance of the Oldowan.

Acknowledgements

The authors thank Claudio Tennie for reading an earlier version of the paper. Reeves also thanks the STONECULT Project for supporting his research. The project STONECULT has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 714658).

References

Andrefsky, William. 2008. "Raw-Material Availability and the Organization of Technology." *Amerian Antiquity* 59 (1): 21–34.

———. 2009. "The Analysis of Stone Tool Procurement, Production, and Maintenance." *Journal of Archaeological Research* 17 (1): 65–103. https://doi.org/10.1007/s10814-008-9026-2.

Bamforth, Douglas B. 1990. "Settlement, Raw Material, and Lithic Procurement in the Central Mojave Desert." *Journal of Anthropological Archaeology* 9 (1): 70–104. https://doi.org/10.1016/0278-4165(90)90006-Y.

Bamforth, Douglas B. 1986. "Technological Efficiency and Tool Curation." *American Antiquity* 51 (1): 38–50. https://doi.org/10.2307/280392.

Barham, Lawrence, and Peter Mitchell. 2008. *The First Africans: African Archaeology from the Earliest Tool Makes to Most Recent Foragers*. Cambridge University Press.

Behrensmeyer, A. K., R. Potts, Thomas W. Plummer, L. Tauxe, N. Opdyke, and T. Jorstad. 1995. "The Pleistocene Locality of Kanjera, Western Kenya: Stratigraphy, Chronology and Paleoenvironments." *Journal of Human Evolution* 29 (3): 247–74. https://doi.org/10.1006/jhev.1995.1059.

Binford, Lewis R. 1976. "Contemporary Model Building: Paradigms and the Current State of Palaeolithic Research." In *Models in Archaeology*, edited by David L. Clarke, 18. London: Routledge. https://doi.org/10.1590/S1516-18462008000300012.

———. 2001. *Constructing Frames of Reference*. San Fransisco: University of California Press.

Bishop, Laura C., Thomas W. Plummer, Joseph V. Ferraro, David R. Braun, Peter W. Ditchfield, Fritz Hertel, John D. Kingston, Jason Hicks, and Richard Potts. 2006. "Recent Research into Oldowan Hominin Activities at Kanjera South , Western Kenya." *African Archaeological Review* 23: 31–40. https://doi.org/10.1007/s10437-006-9006-1.

Blumenschine, R.J., and C.R. Peters. 1998. "Archaeological Predictions for Hominid Land Use in the Paleo-Olduvai Basin, Tanzania, During Lowermost Bed II Times." *Journal of Human Evolution* 34 (6): 565–607. https://doi.org/10.1006/jhev.1998.0216.

Blumenschine, Robert J., Fidelis T. Masao, Joanne C. Tactikos, and James I. Ebert. 2008. "Effects of Distance from Stone Source on Landscape-Scale Variation in Oldowan Artifact Assemblages in the Paleo-Olduvai Basin, Tanzania." *Journal of Archaeological Science* 35 (1): 76–86. https://doi.org/10.1016/j.jas.2007.02.009.

Blumenschine, Robert J., Ian G. Stanistreet, and Fidelis T. Masao. 2012. "Olduvai Gorge and the Olduvai Landscape Paleoanthropology Project." *Journal of Human Evolution* 63 (2): 247–50. https://doi.org/10.1016/j.jhevol.2012.05.005.

Brantingham, P. Jeffrey. 1998. "Mobility, Competition, and Plio-Pleistocene Hominid Foraging Groups." *Journal of Archaeological Method and Theory* 5 (1): 57–98. https://doi.org/10.1007/BF02428416.

———. 2003. "A Neutral Model of Stone Raw Material Procurement." *American Antiquity* 68 (3): 487–509. https://doi.org/10.2307/3557105.

Brantingham, P. Jeffrey, and Steven L Kuhn. 2001. "Constraints on Levallois Core Technology: A Mathematical Model." *Journal of Archaeological Science* 28 (7): 747–61. https://doi.org/10.1006/jasc.2000.0594.

Braun, David R., Vera Aldeias, Will Archer, J. Ramon Arrowsmith, Niguss Baraki, Christopher J. Campisano, Alan L. Deino, et al. 2019. "Earliest Known Oldowan Artifacts at ≫2.58 Ma from Ledi-Geraru, Ethiopia, Highlight Early Technological Diversity." *Proceedings of the National Academy of Sciences* 116 (24): 11712–7. https://doi.org/10.1073/pnas.1820177116.

Braun, David R., Peter Ditchfield, Joseph V. Ferraro, David Maina, Laura C. Bishop, and Richard Potts. 2008. "Oldowan Behavior and Raw Material Transport: Perspectives from the Kanjera Formation." *Journal of Archaeological Science* 35 (8): 2329–45. https://doi.org/10.1016/j.jas.2008.03.004.

Braun, David R., and Jack W.K. Harris. 2003. "Technological Developments in the Oldowan of Koobi Fora: Innovative Techniques of Artifact Analysis." In, 29.

Braun, David R., John W.K. Harris, and David N. Maina. 2009. "Oldowan Raw Material Procurement and Use: Evidence from the Koobi Fora Formation." *Archaeometry* 51: 26–42.

Braun, David R., Thomas W. Plummer, Peter W. Ditchfield, Laura C. Bishop, and Joseph V. Ferraro. 2009. “Oldowan Technology and Raw Material Variability at Kanjera South.” In *Interdisciplinary Approaches to the Oldowan*, 99–110. Vertebrate Paleobiology and Paleoanthropology. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-1-4020-9060-8_9.

Braun, David R., Thomas W. Plummer, Joseph V. Ferraro, Peter Ditchfield, and Laura C. Bishop. 2009. “Raw Material Quality and Oldowan Hominin Toolstone Preferences: Evidence from Kanjera South, Kenya.” *Journal of Archaeological Science* 36 (7): 1605–14. https://doi.org/10.1016/j.jas.2009.03.025.

Braun, David R., Michael J. Rogers, John W.K. Harris, and Steven J. Walker. 2008. “Landscape-Scale Variation in Hominin Tool Use: Evidence from the Developed Oldowan.” *Journal of Human Evolution* 55 (6): 1053–63. https://doi.org/10.1016/j.jhevol.2008.05.020.

Braun, David R., Joanne C. Tactikos, Joseph V. Ferraro, Shira L. Arnow, and John W.K. Harris. 2008. “Oldowan Reduction Sequences: Methodological Considerations.” *Journal of Archaeological Science* 35 (8): 2153–63. https://doi.org/10.1016/j.jas.2008.01.015.

Bunn, Henry, John W.K. Harris, Glynn Isaac, Zefe Kaufulu, Ellen Kroll, Kathy Schick, Nicholas Toth, and Anna K. Behrensmeyer. 1980. “FxJj50: An Early Pleistocene Site in Northern Kenya.” *World Archaeology* 12 (2): 109–36. https://doi.org/10.1080/00438243.1980.9979787.

Burnside, William R., James H. Brown, Oskar Burger, Marcus J. Hamilton, Melanie Moses, and Luis M.A. Bettencourt. 2012. “Human Macroecology: Linking Pattern and Process in Big-Picture Human Ecology.” *Biological Reviews* 87 (1): 194–208. https://doi.org/10.1111/j.1469-185X.2011.00192.x.

Chavaillon, Jean. 1970. “Découverte d’un niveau oldowayen dans la basse vallée de l'Omo (Ethiopie)." *Bulletin de La Société Préhistorique Française* 67 (1). Société Préhistorique Française: 7–11. https://doi.org/10.3406/bspf.1970.10428.

Clark, G. A., and C. Michael Barton. 2017. "Lithics, Landscapes & La Longue-Durée & Expediency as Expressions of Forager Mobility." *Quaternary International* 450: 137–49. https://doi.org/10.1016/j.quaint.2016.08.002.

Clark, J. Desmond. 1975. "Africa in Prehistory: Peripheral or Paramount?" *Man* 10 (2). [Wiley, Royal Anthropological Institute of Great Britain and Ireland]: 175–98. https://doi.org/10.2307/2800493.

Clarkson, Chris. 2013. "Measuring Core Reduction Using 3D Flake Scar Density: A Test Case of Changing Core Reduction at Klasies River Mouth, South Africa." *Journal of Archaeological Science* 40 (12): 4348–57. https://doi.org/10.1016/j.jas.2013.06.007.

Close, Angela E. 1999. "Distance and Decay: An Uneasy Relationship." *Antiquity* 73 (279): 24–32. https://doi.org/10.1017/S0003598X00087810.

Cotterell, B., J. Kamminga, and F. P. Dickson. 1985. "The Essential Mechanics of Conchoidal Flaking." *International Journal of Fracture* 29 (4): 205–21. https://doi.org/10.1007/BF00125471.

Davies, Benjamin, Simon J Holdaway, and Patricia C Fanning. 2018. "Modeling Relationships Between Space, Movement, and Lithic Geometric Attributes." *Amerian Antiquity* American A: 1–18. https://doi.org/10.1017/aaq.2018.23.

Delagnes, A, and H Roche. 2005. "Late Pliocene Hominid Knapping Skills: The Case of Lokalalei 2C, West Turkana, Kenya." *Journal of Human Evolution* 48 (5): 435–72. https://doi.org/10.1016/j.jhevol.2004.12.005.

de la Torre, Ignacio. 2004. "Omo Revisited: Evaluating the Technological Skills of Pliocene Hominids." *Current Anthropology* 45 (4): 439–65. https://doi.org/10.1086/422079.

de la Torre, Ignacio, and Rafael Mora. 2005. *Technological Strategies in* *the Lower Pleistocene at Olduvai Beds I and II*. Liege: Service de Prehistoire, Universite de Liege.

de la Torre Ignacio, I. 2011. "The Early Stone Age Lithic Assemblages of Gadeb (Ethiopia) and the Developed Oldowan/Early Acheulean in East Africa." *Journal of Human Evolution* 60 (6): 768–812. https://doi.org/10.1016/j.jhevol.2011.01.009.

Dibble, Harold. 1995. "Middle Paleolithic Scraper Reduction: Background, Clarification, and Review of the Evidence to Date." *Journal of Archaeological Method and Theory* 2 (4): 299–368.

Ditchfield, P. W., E. Whitfield, T. Vincent, Thomas W. Plummer, David R. Braun, Alan L. Deino, J. S. Oliver, J. Louys, and Laura C. Bishop. 2018. "Geochronology and Physical Context of Oldowan Site Formation at Kanjera South, Kenya." *Geological Magazine*, 1–11. https://doi.org/10.1017/S0016756818000602.

Dogandžić, Tamara, David R. Braun, and Shannon P. McPherron. 2015. "Edge Length and Surface Area of a Blank: Experimental Assessment of Measures, Size Predictions and Utility." *PLoS ONE* 10 (9). https://doi.org/10.1371/journal.pone.0133984.

Douglass, Matthew J. 2010. "The Archaeological Potential of Informal Lithic Technologies: A Case Study of Assemblage Variability in Western New South Wales, Australia." PhD Thesis, Auckland: University of Auckland.

Douglass, Matthew J., Sam C. Lin, David R. Braun, and Thomas W. Plummer. 2017. "Core Use-Life Distributions in Lithic Assemblages as a Means for Reconstructing Behavioral Patterns." *Journal of Archaeological Method and Theory*, 1–35. https://doi.org/10.1007/s10816-017-9334-2.

Eren, Metin I., Aaron Greenspan, and C. Garth Sampson. 2008. "Are Upper Paleolithic Blade Cores More Productive Than Middle Paleolithic Discoidal

Cores? A Replication Experiment.” *Journal of Human Evolution* 55 (6): 952–61. https://doi.org/10.1016/j.jhevol.2008.07.009.

Eren, Metin I., and C. Garth Sampson. 2009. “Kuhn’s Geometric Index of Unifacial Stone Tool Reduction (GIUR): Does It Measure Missing Flake Mass?” *Journal of Archaeological Science* 36 (6): 1243–7. https://doi.org/10.1016/j.jas.2009.01.011.

Ferraro, Joseph V., Thomas W. Plummer, Briana L. Pobiner, James S. Oliver, Laura C. Bishop, David R. Braun, Peter W. Ditchfield, et al. 2013. “Earliest Archaeological Evidence of Persistent Hominin Carnivory.” *PLOS ONE* 8 (4): e62174. https://doi.org/10.1371/journal.pone.0062174.

Foley, Robert. 1981a. “A Model of Regional Archaeological Structure.” *Proceedings of the Prehistoric Society* 1-17: 1–17.

———. 1981b. “Off-Site Archaeology: An Alternative Approach for the Short-Sited.” In *Pattern of the Past: Studies in Honour of David Clarke*, 33:139–53. Cambridge: Cambridge University Press.

Gallotti, Rosalia. 2018. “Before the Acheulean in East Africa: An Overview of the Oldowan Lithic Assemblages.” In *The Emergence of the Acheulean in East Africa and Beyond*, edited by Rosalia Gallotti and Margherita Mussi, 13–32. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-75985-2_2.

Harmand, Sonia. 2009. “Variability in Raw Material Selectivity at the Late Pliocene Sites of Lokalalei, West Turkana, Kenya.” In *Interdisciplinary Approaches to the Oldowan*, edited by Erella Hovers and David R. Braun, 85–97. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-1-4020-9060-8_8.

Harris, John William Kendal. 1978. “The Karari Industry, Its Place in East African Prehistory.” PhD Thesis, Univversity of California, Berkeley.

Hay, Richard LeRoy. 1976. *Geology of the Olduvai Gorge*. Los Angeles: University of California Press.

Holdaway, Simon, Nicola Stern, and Parth R. Chauhan. 2004. "A Record in Stone. The Study of Australia's Flaked Stone Artefacts."

Hovers, Erella. 2012. "Invention, Reinvention and Innovation." In *Developments in Quaternary Sciences*, 16:51–68. Elsevier. https://doi.org/10.1016/B978-0-444-53821-5.00005-1.

Inizan, Marie-Louise, Michèle Reduron-Ballinger, Hélène Roche, Jacques Tixier, and Jehanne Féblot-Augustins, eds. 1999. *Technology and Terminology of Knapped Stone: Followed by a Multilingual Vocabulary - Arabic, English, French, German,Greek, Italian, Portuguese, Spanish.* Préhistoire de La Pierre Taillée 5. Nanterre: CREP.

Iovita, Radu, and Shannon P. McPherron. 2011. "The Handaxe Reloaded: A Morphometric Reassessment of Acheulian and Middle Paleolithic Handaxes." *Journal of Human Evolution* 61 (1): 61–74. https://doi.org/10.1016/j.jhevol.2011.02.007.

Isaac, Glynn. 1984. "The Archaeology of Human Origins: Studies of the Lower Pleistocene in East Africa, 1971-1981." In *Advances in World Archaeology*, 1–86.

Isaac, Glynn Ll. 1981. "Stone Age Visiting Cards: Approaches to the Study of Early Land Use Patterns." In *Pattern of the Past: Studies in Honour of David Clarke*, 131–55. Cambridge: University of Cambridge Press.

Isaac, Glynn L.L. 1983. "Bones in Contention: Competing Explanations for the Juxtaposition of Early Pleistocene Artefacts and Faunal Remains." In *Animals in ArchaeoloftL Hunters and Their Prey*, 3–19. Oxford: British Archaeological Reports.

Isaac, Glynn Ll., and John W.K. Harris. 1976. "The Scatter Between the

Patches." In *The Krober Anthropological Society*. Berkeley: Unpublished.

Isaac, Glynn Llwelyn, and Barbara Isaac. 1997. *Koobi Fora Research Project. "Koobi Fora Research Project Vol. 5: Plio-Pleistocene Archaeology*. Oxford: Oxford University Press.

Keeley, Lawrence H., and Nicholas Toth. 1981. "Microwear Polishes on Early Stone Tools from Koobi Fora, Kenya." *Nature* 293 (5832): 464–65. https://doi.org/10.1038/293464a0.

Kent, P. E. 1942. "The Pleistocene Beds of Kanam and Kanjera, Kavirondo, Kenya." *Geological Magazine* 79 (2): 117–32. https://doi.org/10.1017/S001675680007360X.

Kimbel, W.H., R.C. Walter, D.C. Johanson, K.E. Reed, J.L. Aronson, Z. Assefa, C.W. Marean, et al. 1996. "Late Pliocene Homo and Oldowan Tools from the Hadar Formation (Kada Hadar Member), Ethiopia." *Journal of Human Evolution* 31 (6): 549–61. https://doi.org/10.1006/jhev.1996.0079.

Kuhn, Steven L., David A. Raichlen, and Amy E. Clark. 2016. "What Moves Us? How Mobility and Movement Are at the Center of Human Evolution." *Evolutionary Anthropology* 25 (3): 86–97. https://doi.org/10.1002/evan.21480.

la de Torre, Ignacio, and Rafael Mora. 2009. "Remarks on the Current Theoretical and Methodological Approaches to the Study of Early Technological Strategies in Eastern Africa." In *Interdisciplinary Approaches to the Oldowan*, edited by Erella Hovers and David R. Braun, 15–24. Vertebrate Paleobiology and Paleoanthropology. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-1-4020-9060-8_2.

Leakey, Mary. 1971. *Olduvai Gorge Vol. 3 Beds I and II*. Cambridge: Cambridge University Press.

Lemorini, Cristina, Laura C. Bishop, Thomas W. Plummer, David R. Braun, Peter W. Ditchfield, and James S. Oliver. 2019. "Old Stones' SongSecond

Verse: Use-Wear Analysis of Rhyolite and Fenetized Andesite Artifacts from the Oldowan Lithic Industry of Kanjera South, Kenya.” *Archaeological and Anthropological Sciences* 11 (9): 4729–54. https://doi.org/10.1007/s12520-019-00800-z.

Lemorini, Cristina, Thomas W. Plummer, David R. Braun, Alyssa N. Crittenden, Peter W. Ditchfield, Laura C. Bishop, Fritz Hertel, et al. 2014. “Old Stones’ Song: Use-Wear Experiments and Analysis of the Oldowan Quartz and Quartzite Assemblage from Kanjera South (Kenya).” *Journal of Human Evolution* 72 (July): 10–25. https://doi.org/10.1016/j.jhevol.2014.03.002.

Lin, Sam C., Zeljko Rezek, David Braun, and Harold L. Dibble. 2013. “On the Utility and Economization of Unretouched Flakes: The Effects of Exterior Platform Angle and Platform Depth.” *American Antiquity* 78 (4): 724–45. https://doi.org/10.2307/43184970.

Ludwig, Brian V, and J W K Harris. 1998. “Towards a Technological Reassessment of East African Plio-Pleistocene Lithic Assemblages.” In *Early Human Behavior in Global Context: The Rise of Diversity of the Lower Palaeolithic Period*, edited by Ravi Korisettar and Michael D. Petraglia, 23. New York: Routledge.

Moore, Mark W., and Yinika Perston. 2016. “Experimental Insights into the Cognitive Significance of Early Stone Tools.” Edited by Michael D. Petraglia. *PLOS ONE* 11 (7): e0158803. https://doi.org/10.1371/journal.pone.0158803.

Morgan, T. J. H., N. T. Uomini, L. E. Rendell, L. Chouinard-Thuly, S. E. Street, H. M. Lewis, C. P. Cross, et al. 2015. “Experimental Evidence for the Co-Evolution of Hominin Tool-Making Teaching and Language.” *Nature Communications* 6 (1): 1–8. https://doi.org/10.1038/ncomms7029.

Muller, Antoine, and Chris Clarkson. 2016. “Identifying Major Transitions in the Evolution of Lithic Cutting Edge Production Rates.” Edited by Roberto

Macchiarelli. *PLOS ONE* 11 (12): e0167244. https://doi.org/10.1371/journal.pone.0167244.

Nelson, Margaret C. 1991. “The Study of Technological Organization.” *Archaeological Method and Theory* 3: 57–100.

Newman, Jay R. 1994. “The Effects of Distance on Lithic Material Reduction Technology.” *Journal of Field Archaeology* 21 (4): 491–501. https://doi.org/10.1179/009346994797175541.

Oliver, James S., Thomas W. Plummer, Fritz Hertel, and Laura C. Bishop. 2019. “Bovid Mortality Patterns from Kanjera South, Homa Peninsula, Kenya and FLK-Zinj, Olduvai Gorge, Tanzania: Evidence for Habitat Mediated Variability in Oldowan Hominin Hunting and Scavenging Behavior.” *Journal of Human Evolution* 131 (June): 61–75. https://doi.org/10.1016/j.jhevol.2019.03.009.

Peters, C R, and R J Blumenschine. 1995. “Landscape Perspectives on Possible Land Use Patterns for Early Pleistocene Hominids in the Olduvai Basin, Tanzania.” *Journal of Human Evolution* 29: 321–62.

Plummer, Thomas W. 2004. “Flaked Stones and Old Bones: Biological and Cultural Evolution at the Dawn of Technology.” *Yearbook of Physical Anthropology* 47: 118–64. https://doi.org/10.1002/ajpa.20157.

Plummer, Thomas W., and Laura C. Bishop. 2016. “Oldowan Hominin Behavior and Ecology at Kanjera South, Kenya.” *Journal of Anthropological Sciences*, no. 94: 29–40. https://doi.org/10.4436/JASS.94033.

Plummer, Thomas W., Laura C. Bishop, Peter W. Ditchfield, Joseph V. Ferraro, John D. Kingston, Fritz Hertel, and David R. Braun. 2009. “The Environmental Context of Oldowan Hominin Activities at Kanjera South, Kenya.” In *Interdisciplinary Approaches to the Oldowan*, edited by Erella Hovers and David R. Braun, 149–60. Vertebrate Paleobiology and Paleoanthropology. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-1-4020-9060-8_12.

Plummer, Thomas W., Laura C. Bishop, Peter W. Ditchfield, and Jason Hicks. 1999. "Research on Late Pliocene Oldowan Sites at Kanjera South, Kenya." *Journal of Human Evolution* 36 (2): 151–70. https://doi.org/10.1006/jhev.1998.0256.

Plummer, Thomas W., Peter W. Ditchfield, Laura C. Bishop, John D. Kingston, Joseph V. Ferraro, David R. Braun, Fritz Hertel, and Richard Potts. 2009. "Oldest Evidence of Toolmaking Hominins in a Grassland-Dominated Ecosystem." *PLoS ONE* 4 (9). https://doi.org/10.1371/journal.pone.0007199.

Plummer, Thomas W., Joseph Ferraro, Peter Ditchfield, Laura Bishop, and Richard Potts. 2001. "Late Pliocene Oldowan Excavations at Kanjera South, Kenya." *Antiquity* 75 (290): 809–10. https://doi.org/10.1017/S0003598X00089365.

Plummer, Thomas W., and Emma M. Finestone. 2018. "3 Archaeological Sites from 2.6 - 2.0 Ma: Toward a Deeper Understanding of the Early Oldowan." In. February.

Pop, Cornel M. 2016. "Simulating Lithic Raw Material Variability in Archaeological Contexts: A Re-Evaluation and Revision of Brantingham's Neutral Model." *Journal of Archaeological Method and Theory* 23 (4): 1127–61. https://doi.org/10.1007/s10816-015-9262-y.

Potts, Richard. 1991. "Why the Oldowan? Plio-Pleistocene Toolmaking and the Transport of Resources." *Journal of Anthropological Research* 47 (2): 153–76. https://doi.org/10.1086/jar.47.2.3630323.

Pruetz, Jill, and Paco Bertolani. 2009. "Chimpanzee (Pan Troglodytes Verus) Behavioral Responses to Stresses Associated with Living in a Savannah-Mosaic Environment: Implications for Hominin Adaptations to Open Habitats." *PaleoAnthropology* 2009: 252–62. https://doi.org/10.4207/PA.2009.ART33.

Reeves, Jonathan S. 2019. "Digital Stone Age Visiting Cards: Quantitative Approaches to Early Pleistocene Hominin Land Use." PhD Thesis, Washington

D.C.: George Washington University.

Roche, H., A. Delagnes, J.-P. Brugal, C. Feibel, M. Kibunjia, V. Mourre, and P.-J. Texier. 1999. "Early Hominid Stone Tool Production and Technical Skill 2.34 Myr Ago in West Turkana, Kenya." *Nature* 399 (6731): 57–60. https://doi.org/10.1038/19959.

Roche, Hélène, Robert J. Blumenschine, and John J. Shea. 2009. "Origins and Adaptations of Early Homo: What Archeology Tells Us." In *The First Humans and Early Evolution of the Genus Homo*, edited by Frederick E. Grine, John G. Fleagle, and Richard E. Leakey, 135–47. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-1-4020-9980-9_12.

Roche, Hélène, Ignacio de la Torre, Adrian Arroyo, Jean-Philip Brugal, and Sonia Harmand. 2018. "Naiyena Engol 2 (West Turkana, Kenya): A Case Study on Variability in the Oldowan." *African Archaeological Review* 35 (1): 57–85. https://doi.org/10.1007/s10437-018-9283-5.

Rogers, Michael J., John W.K. Harris, and Craig S. Feibel. 1994. "Changing Patterns of Land Use by Plio-Pleistocene Hominids in the Lake Turkana Basin." *Journal of Human Evolution* 27: 139–58.

Rogers, Michael John. 1997. "A Landscape Archaeological Investigation at East Turkana, Kenya." PhD Thesis, Rutgers.

Schick, Kathy D, and Nicholas Patrick Toth. 1994. *Making Silent Stones Speak: Human Evolution and the Dawn of Technology.* Simon and Schuster.

Sellet, Frédéric. 1993. "Chaine Operatoire; the Concept and Its Applications." *Lithic Technology* 18 (1-2): 106–12. https://doi.org/10.1080/01977261.1993.11720900.

Semaw, Sileshi. 2000. "The World's Oldest Stone Artefacts from Gona, Ethiopia: Their Implications for Understanding Stone Technology and Patterns of Human Evolution Between 2·61·5 Million Years Ago." *Journal of Archaeological*

Science 27 (12): 1197–1214. https://doi.org/10.1006/jasc.1999.0592.

Shick, Kathy D. 1987. “Modeling the Formation of Early Stone Age Artifact Concentrations.” *Journal of Human Evolution* 16 (7-8): 789–807. https://doi.org/10.1016/0047-2484(87)90024-8.

Shott, Michael J. 1996. “An Exegesis of the Curation Concept.” *Journal of Anthropological Research* 52 (3): 259–80. https://doi.org/10.1086/jar.52.3.3630085.

Shott, Michael J, and Paul Sillitoe. 2004. “Modeling Use-Life Distributions in Archaeology Using New Guinea Wola Ethnographic Data.” *Amerian Antiquity* 69 (2): 339–55.

Soressi, Marie, and Jean-Michel Geneste. 2011. “Reduction Sequence, Chane Opératoire, and Other Methods: The Epistemologies of Different Approaches to Lithic Analysis the History and Efficacy of the Chane Opératoire Approach to Lithic Analysis: Studying Techniques to Reveal Past Societies in an Evolutionary Perspective.” *PaleoAnthropology* 334: 350.

Stern, Nicola, Nicholas Porch, and Ian Mcdougall. 2002. “FxJj43 : A Window into a 1 . 5-Million- Year-Old Palaeolandscape in the Okote Member of the Koobi Fora Formation , Northern Kenya.” *Geoarchaeology* 17 (4): 349–92. https://doi.org/10.1002/gea.10018.

Stout, Dietrich, and Thierry Chaminade. 2009. “Making Tools and Making Sense: Complex, Intentional Behaviour in Human Evolution.” *Cambridge Archaeological Journal* 19 (1): 85–96. https://doi.org/10.1017/S0959774309000055.

Stout, Dietrich, Erin Hecht, Nada Khreisheh, Bruce Bradley, and Thierry Chaminade. 2015. “Cognitive Demands of Lower Paleolithic Toolmaking.” Edited by Nuno Bicho. *PLOS ONE* 10 (4): e0121804. https://doi.org/10.1371/journal.pone.0121804.

Stout, Dietrich, Jay Quade, Sileshi Semaw, Michael J. Rogers, and Naomi

E. Levin. 2005. “Raw Material Selectivity of the Earliest Stone Toolmakers at Gona, Afar, Ethiopia.” *Journal of Human Evolution* 48 (4): 365–80. https://doi.org/10.1016/j.jhevol.2004.10.006.

Stout, Dietrich, Michael J. Rogers, Adrian V. Jaeggi, and Sileshi Semaw. 2019. “Archaeology and the Origins of Human Cumulative Culture: A Case Study from the Earliest Oldowan at Gona, Ethiopia.” *Current Anthropology*, April, 000–000. https://doi.org/10.1086/703173.

Stout, Dietrich, Sileshi Semaw, Michael J. Rogers, and Dominique Cauche. 2010. “Technological Variation in the Earliest Oldowan from Gona, Afar, Ethiopia.” *Journal of Human Evolution* 58 (6): 474–91. https://doi.org/10.1016/j.jhevol.2010.02.005.

Tennie, Claudio, David R. Braun, L. S. Premo, and Shannon P. McPherron. 2016. “The Island Test for Cumulative Culture in the Paleolithic.” In *The Nature of Culture*, edited by Miriam N. Haidle, Nicholas J. Conard, and Michael Bolus, 121–33. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-017-7426-0_11.

Tennie, Claudio, L. S. Premo, David R. Braun, and Shannon P. McPherron. 2017. “Early Stone Tools and Cultural Transmission: Resetting the Null Hypothesis.” *Current Anthropology* 58 (5): 000–000. https://doi.org/10.1086/693846.

Toth, Nicholas. 1982. “The Stone Technologies of Early Hominids at Koobi Fora, Kenya: An Experimental Approach.” Doctoral Dissertation, Univversity of California, Berkeley.

———. 1985. “The Oldowan Reassessed: A Close Look at Early Stone Artifacts.” *Journal of Archaeological Science* 12 (2): 101–20. https://doi.org/10.1016/0305-4403(85)90056-1.

———. 1987. “Behavioral Inferences from Early Stone Artifact Assemblages : An Experimental Model.” *Journal of Human Evolution* 16: 763–87.

Toth, Nicholas, and Kathy Schick. 2006. *The Oldowan: Case Studies into the Earliest Stone Age*. Bloomington: Stone Age Institute Press.

———. 2018. “An Overview of the Cognitive Implications of the Oldowan Industrial Complex.” *Azania: Archaeological Research in Africa* 53 (1): 3–39. https://doi.org/10.1080/0067270X.2018.1439558.

Whiten, A., J. Goodall, W. C. McGrew, T. Nishida, V. Reynolds, Y. Sugiyama, C. E. G. Tutin, R. W. Wrangham, and C. Boesch. 1999. “Cultures in Chimpanzees.” *Nature* 399 (6737): 682–85. https://doi.org/10.1038/21415.

Whiten, Andrew, Kathy Schick, and Nicholas Toth. 2009. “The Evolution and Cultural Transmission of Percussive Technology: Integrating Evidence from Palaeoanthropology and Primatology.” *Journal of Human Evolution* 57 (4): 420–35. https://doi.org/10.1016/j.jhevol.2008.12.010.

Wynn, Thomas, and Frederick L. Coolidge. 2016. “Archeological Insights into Hominin Cognitive Evolution.” *Evolutionary Anthropology: Issues, News, and Reviews* 25 (4): 200–213. https://doi.org/10.1002/evan.21496.