Ecological perspectives on technological diversity at Kanjera South

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**Abstract**

The aspects of hominin behavior responsible for Oldowan stone tool variation are 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 Kanjera South, Kenya provide an opportunity to examine the interaction 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 reflect a dynamic relationship between raw material properties, provenance, and hominin mobility. Exotic raw materials are generally more resistant to edge attrition compared to those available locally, which may have incentivized their transport over long distances. 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 in 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. Moreover, the variation in stone tool reduction is not consistent with neutral models of stone tool transport and discard. 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. 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.

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# 1. Introduction

Upon its initial discovery, the Oldowan was considered an expedient industry that was akin to simply smashing stones. Nearly a century later, the Oldowan is considered to reflect a complex behavioral pattern that encompasses not only the technical capacity to efficiently produce flakes, but also dynamic patterns of transport. 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 (Semaw et al., 2000; de la Torre, 2004; Delagnes and Roche, 2005; Stout et al., 2005; Schick et al., 2006; Braun et al., 2009b, 2019). This pattern of tool production was integrated into a broader land-use strategy in which raw material is acquired, transported, utilized, maintained and eventually discarded (Hay, 1976; Isaac and Harris, 1976; Isaac, 1981, 1984; Toth, 1985, 1987; Schick, 1987; Potts, 1991, 1994; Blumenschine and Peters, 1998; Potts et al., 1999; Blumenschine et al., 2008; Braun et al., 2008a). Though these actions remained simple, the various ways in which they are combined create a variety of production strategies that can be evaluated on a site-by-site basis (Delagnes and Roche, 2005).

Research over the last two decades has revealed a multitude of technological diversity in the Oldowan across time and space. A primary objective of current Oldowan research is identifying the behavioral processes in which such a diversity of production strategies arise (Plummer, 2004; Roche et al., 2009; Gallotti, 2018). A multitude of work now links the technical diversity of the Oldowan to the performance of individual or a group of tool makers, cognition, and social learning mechanisms (Schick and Toth, 1994; Stout and Chaminade, 2009; Stout, 2011; Roche et al., 2018; Toth and Schick, 2018; Stout et al., 2019). In addition, stone tool diversity is linked to constraints imposed by raw material geometry, quality, abundance, and transport (Toth, 1985, 1987; Potts, 1991; de la Torre, 2004; Blumenschine et al., 2008; Braun et al., 2009a). Some research has gone as far to suggest that the technological diversity in the Oldowan merely reflects different levels of reduction intensity (Toth, 1985; Potts, 1991; Moore and Perston, 2016). Though the possibility of this notion has been demonstrated in experimental contexts (Toth, 1985; Moore and Perston, 2016), it has seldom been tested in the archaeological record.

The 2.0 ma site of Kanjera South has the potential to contribute to our understanding of the relationship between stone tool production, technical decision making and the broader landscape. The lithic assemblage at Kanjera South shows a substantial representation of exotic raw materials and a diversity of different core reduction strategies that provide an opportunity to understand the technical decision making within the context of broader hominin land-use strategies. To this end, we present a novel study of the Kanjera South lithic material that combines previous analyses of raw material properties, provenance, and technology with quantitative measures of core reduction intensity and tool utilization to elucidate the broader land-use pattern. -technological an.

The results of this study provide insight into hominin land-use, lithic reduction, and technological diversity, and expand our understanding of hominin land-use. Although early Oldowan assemblages dating to 2.0 million years ago and older seem to illustrate a similar level of technological competence to those from later timeframes, substantially less is known about the broader foraging behaviors and land-use strategies of hominins during this interval. An investigation of hominin stone tool transport and utilization patterns at Kanjera would not only add to our understanding of how the landscape structures stone tool behavior, but also shed light on hominin land-use patterns during the early Oldowan.

# 2.0 Background to Kanjera South

***Insert* Figure 2**

The 2.0 Ma 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 et al., 1999; Ditchfield et al., 2019, figure 2). The extensive excavation of a 3 meter deep sequence of silts and clays recovered over 3000 fossils and similar numbers of stone artifacts (Plummer et al., 2009a). The stratigraphy at Kanjera South is made up of approximately 30 meters of fluvial, colluvial and lacustrine sediments (Ditchfield et al. 2018). Extensive research on the geochronology and sedimentary context has demonstrated that the lithics and fossils accumulated predominantly due to hominin activity (Behrensmeyer et al., 1995; Plummer et al., 2009a, 2009b; Ferraro et al., 2013; Ditchfield et al., 2019). and enamel isotope studies landscape surrounding et al., 2009a, 2009b; Z South and mixed access to larger carcasses (Oliver et al., 2019), and this record is consistent through the stratified sequence, suggesting that persistent carnivory spanned hundreds to thousands of years (Ferraro et al. 2013)

Extensive geological surveys of the Homa Peninsula and the surrounding area reveal a high diversity of igneous and metamorphic rocks that provided a wide range of suitable materials that hominins could utilize for flake production (Saggerson, 1952; Le Bas, 1977; Braun et al., 2008; Finestone et al., 2020). As such, this diversity is reflected in the lithic assemblage. More than 16 different rock types are represented in the assemblage but the bulk of the material is produced on 8 of them (Braun et al., 2008). Geochemical finger printing of the lithic material makes it possible to further subdivide the lithic assemblage to two broad categories of raw material provenance: local and exotic (table 1; Braun et al., 2008). Local materials suggest are derived from the Homa Mountain Carbonatite center (Figure 2). Drainages running off the flanks of this mountain would have carried materials such as phonolite, limestone, and fenetized rocks within the immediate vicinity of Kanjera South. Sources of the exotic materials, such as quartzite, rhyolite, andesite, and granite are located more inland from Lake Victoria in places such as the Kisi Highlands and Oyugis (Figure 2). While these materials were likely acquired from river channels traveling west-ward toward Kanjera South, they are not present in Pleistocene river conglomerates within 10 kilometers of Kanjera South (Braun et al., 2008).

Kanjera South is not only unique the number of raw material represented, but also the diversity of technological production strategies present within the assemblage. Unlike most other Oldowan sites from this timeframe, the flake production strategies range from simple unifacial techniques to bifacial and multifacial techniques. Previous work has suggested that some this diversity reflects the differences in the quality of available raw materials or the need to maximize the amount of flakes removed from a high quality materials (Braun et al., 2009a). The wide range in diversity of materials from local and exotic sources, and technological reduction strategies, provide an opportunity to investigate the dynamics between hominin land-use patterns, stone tool production, and Oldowan assemblage variability.

**Insert Figure 3**

# 2. Materials and methods

*2.1 Materials*

To explore the relationship between stone tool transport and Oldowan assemblage variability, wexotic (Table 2) Preexisting knowledge regarding raw material provenance, raw material properties, and core exploitation strategies (Braun et al., 2008; Braun et al., 2009a) was combined with an in-depth analysis of the lithic material designed to quantify the intensity of stone tool utilization prior to their discard at Kanjera South.

A total of 1500 stone artifacts (171 cores and 1329 flakes) were characterized using a series of continuous and ordinal variables. Table XX provides a detailed summary of the number of lithics per raw material included. In addition to the previously published technological analysis, the cores were also categorized using the commonly used diachritic types defined by de la Torra and Mora (de la Torre and Mora, 2005). These data were then used to predict the reduction intensity of the cores and the flake sequence number of the flakes.

*2.2 Estimating Core Reduction Intensity*

The reduction intensity of cores influences a variety of attributes that interact throughout the reduction sequence (Douglass et al., 2018) Oldowan and Acheulean core reduction intensity are understood from a diversity of variables ranging from mass, the number of flake scars, to more sophisticated methods that use linear models to estimate the degree to which a core has been reduced. Simple measures such as mass and the number of flake scars are not always appropriate because nodules selected for exploitation are sometimes not similar in size. This is particularly the case at Kanjera South, where toolstones originate from a variety of sources and can vary substantially in size. The number of flake scars does not reflect a 1 to 1 relationship with reduction intensity, because the continuous removal of flakes erases evidence of previous removals (Moore and Perston, 2016). As a result, multi-variate estimates of core reduction intensity provide a way to consider a suite of variables in tandem.



Here we follow methods outlined by Douglass et al. (2018) to estimate the reduction intensity of individual cores in terms of the proportion of mass lost prior to its discard using a predictive generalized linear model. This model was developed based on the experimental reduction of cobbles collected from the Homa Peninsula, specifically to estimate the reduction intensity of cores recovered from Kanjera South. Estimates of core reduction intensity are accurate within an error range of 10%, and application to a subset of the cores from the Kanjera South assemblage suggests that the model is generally applicable to the broader Kanjera South assemblage. In its estimation of core reduction intensity, the 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. Although the definition of the aforementioned attributes are outlined in Douglass et al. (2018), they are worth summarizing here. 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). Therefore, 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 et al., 1985). Thus, as a core approaches exhaustion, the platform angles on the core are likely to approach 90°. More details regarding the specification of the model and lithic attributes it considers can be found in Douglass et al. (2018).

## 2.2. Flake Sequence Estimates

Flake sequence can be general defined as the order number that a given flake was removed from the core. It is a complimentary measure to core reduction intensity as it examines the influence of core reduction on the flake assemblage. The distribution of flake sequence values within an assemblage can provide insight into the relationship between stone tool transport and assemblage formation. For example, if sequence values from the beginning of the reduction sequence (i.e. the 1st, 2nd, 3rd flakes removed) are absent from the flake assemblage this could indicate that early stage flakes were discarded prior to the core’s arrival at the site, or were removed off site. In the Early Stone Age, flake sequences are most commonly characterized using a six-category classification system (more colloquially known as Toth types), based on the on the presence of cortex on a flake’s platform and dorsal surface (Toth, 1985).

Here we follow Braun et al. (2008), which uses 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 Braun et al. (2008: 2156, Fig 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 (Braun et al., 2008b). 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 (Braun et al., 2008b). Therefore, while information derived from individual flake sequence estimates may be coarse-grained, it remains useful for assemblage scale comparisons.

## 2.3. Edge to mass ratio

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. For this measure, we only include rock types that have greater than 50 flakes because the wide variance in values seen in this measure results in wildly divergent values in small samples. These aggregate measures are likely more reflective of the generalized pattern of efficiency in tool production over time at the Kanjera South locality.

2.4 *Statistical comparisons*

The following comparisons were made to elucidate the broader land-use strategy of the Kanjera South hominins: To examine the influence of raw material provenance and transport on core utilization, core reduction intensity values and flake sequence values were compared according to raw material type. The significance of these differences was tested using a Kruskal-Wallis and significant differences were determined using a *p-value* threshold of .05 (Gotelli and Ellison, 2013). To examine whether land-use strategy had an effect on the core reduction strategies employed at Kanjera South, the representation of diacritic reduction types was compared by raw material type. A chi-squared test was used to test the significance of these differences. Finally, core reduction intensity values were also analyzed according to raw material type. A Kruskal-Wallis was used to assess the significance of these differences.

# 3. Results

## 3.1. Core Utilization

Core reduction intensity estimates reveal a wide range of variation in the amount of mass removed from the cores at Kanjera South. Some 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* < 0.0001). 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* < 0.001; Fig. 4).

Insert Figure 4

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* < 0.001). The largest differences are, again, 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 (Fig. 5), while flakes from the locally found materials are from earlier stages of reduction.

Interestingly, there is a striking amount of homogeneity in the distribution of flake sequence values associated with exotic or distant raw materials. With the exception of 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 other exotic materials, its median is quite similar. The 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.

Insert Figure 5

As previously reported (Braun et al., 2009), the Kanjera core assemblage is comprised of a wide variety of technological types and core reduction strategies. The frequency of core reduction strategies present has a significant relationship with the raw material type (Fishers exact test, *p* < 0.001). 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 (Fig. 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 (Fig. ). Contrary to this general pattern, cores produced with the local material Homa Limestone (HLi) are often multifacially reduced. However, as addressed in the discussion, this is likely related to the properties of the raw material itself .

When the core reduction intensity values for each reduction strategy are considered, unifacial and unipolar cores are reduced less than bifacial, multifacial or polyhedral cores (Kruskal Wallis, *p* < .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 that involved more complex patterns of rotation.

Insert Figure 6

## 3.2. Flake efficiency

Analysis of the relative proportion of flake edge to mass indicates significantly different technological strategies applied to the different raw materials from the Kanjera South assemblage. Although the mean values of raw materials are relatively similar, the overall distribution indicates that rock types from sources that are further away from Kanjera South (e.g. NyR, BFe, BQu) are produced in a way that allows for much higher efficiency values than those seen in the rock types found close to Kanjera South (e.g. HLi and FNy, *p* < 0.001 for all pairwise comparisons between HLi and all BQu rock types; *p* <0.001 for all comparisons between FNy and all other rock types. Kruskal-Wallis Rank Sum test, Chi2 = 312.70, df = 5, pairwise comparisons between raw materials use Dunn’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 overlap (Fig. 7). 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 wildly divergent values in small samples.

Insert Figure 7

# 4. Discussion

*Inferring land-use at Kanjera South*

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. This is also reflected in the flake sequence data. To some extent, this can be explained by the poor quality of some of the local materials. As discussed in Braun et al. (2009a), removal sequences in local fenetized rocks (FNy) tend to be short because of the presence of preexisting internal fracture planes within the material. The chalky nature and block-like geometry of Homa limestone (HLi) also limits the number of flakes that can be removed.

However, differences in material properties do not explain all of the differences in reduction intensity between local and exotic materials. Not all of the cores from local sources have internal flaws. In particular, Homa phonolite does not have the defects common in the other local raw materials but is still less reduced than the nonlocal raw materials. In addition, the coarse grained nature of Oyugis granite, makes it difficult to maintain angles of less than 90 degrees, thus limiting the degree that the material could be reduced (Braun et al., 2009). Despite these limitations, Oyugis granite is still more reduced than any of the local raw materials (Fig. 4). The totality of these data suggest that raw material properties do not explain all of the variation in the Kanjera South assemblage.

Differences in stone reduction intensity may be the result of the continuous use of exotic materials as they are moved across the landscape. This is supported by the absence of flake sequence values from early stages of reduction in the non-local assemblage. In terms of land-use, this is consistent with a distance-decay pattern of tool-use (Newman, 1994; Close, 1999). Modeling work has demonstrated that differences in the reduction intensity of materials from local and distant sources can arise in the absence of a structured land-use pattern (Brantingham, 2003; Pop, 2016). However, the Kanjera South assemblage deviates from these neutral models in one critical aspect. Nmodelspredict that with distance from the (Brantingham, 2003, p. 501)In contrast with model expectations, while exotic materials are reduced 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. 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; Braun 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 et al., 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. This is not to say that hominins carried rocks directly to Kanjera South. However, the site may have acted as an attractor on the landscape where hominins frequently visited to carry out stone tool-using behaviors.

This concept 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 demonstrate that hominins carried out a variety of resource processing activities with stone artifacts 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 suggest that hominins spent a great deal of time producing stone tools for a variety of tasks. Furthermore, the lithics included in this study were excavated from a 3 meter sequence suggesting that the patterns evinced by this study are the result of the repeated visitation by hominins over many generations. This further attests to the influence of landscape structure on the foraging ecology of hominin tool makers and the formation Oldowan lithic assemblages over the long term. In the future, it would be interesting to determine if there was something unique about the location of Kanjera South specifically or whether patterns reflect a more general attraction to the Homa Pennisula. However, substantial faulting in the region makes it difficult to place Kanjera South within a broader landscape context.

While the notion that hominins directed their movement toward specific localities or ecotones has been suggested at other localities (you should cite these papers here), Kanjera South represents the earliest documented evidence of this pattern. O

The land-use pattern elucidated at Kanjera South also differs from other Oldowan sites in scale. The pattern described at Koobi Fora (cite) suggests that hominins directed their movements across paleogeographic settings at a scale of hundreds of meters. At Olduvai Gorge, the directed movement toward riparian woodlands is thought to have occurred over a scale of 5 kilometers (cite). The data presented here imply that a pattern of directed movement occurs at a scale of at least 10-13 kilometers for non-local materials. This is an interesting distinction because Kanjera South is the only site from this time frame situated in an open grassland (Plummer et al., 2009). Modern humans tend to travel farther and more frequently in open arid environments than those that live in more productive environments (Burnside et al., 2012) and savanna-adapted chimpanzees from Fongoli, Senegal also possess a larger home range and practice fission-fusion less frequently (Pruetz and Bertolani, 2009). In this respect, the increased scale of land-use pattern at Kanjera South may provide further evidence of the adaptive flexibility of Oldowan hominins in open environments.

*The influence of land-use on Oldowan production strategies*

The results of this study suggest that patterns of land-use influence the technical decisions of Oldowan tool makers. At Kanjera South, exotic raw materials show a strong bias toward more reduced, complete bifacial and multifacial reduction strategies, as opposed to the more even representation of core reduction strategies among local materials. This suggests that the broader pattern of stone tool transport influenced the ways in which Oldowan hominins economized stone. The relatively long transport distance, in combination with the lower quality of material available near Kanjera South, may have incentivized the retention of exotic raw materials in areas where lithologies of such quality were less abundant. In this light, the high frequency of bifacial and multifacial reduction strategies may have arisen from a need to maximize the amount utility that could be extracted from these cores. Similar phenomenon have been documented inframes wherewas

The exploitation of multiple flake removal surfaces allows a core to remain active in a toolkit for a longer period of time.In addition, . This evidence may suggest, that Oldowan hominins at Kanjera south adopted technological strategies that facilitated the transport and use of high quality raw materials across long distances. Therefore, this corpus of information may suggest that Oldowan hominins where able to adopt different technical strategies in order to mitigate the changing qualities in available raw materials over large transport distances. This pattern of exploitation, in the context of the broader land-use strategy at Kanjera South, provides additional evidence for a high level of planning and foresight in Oldowan hominins.

While reduction strategies are often considered to be intentionally applied to cores, it is possible that the various core exploitation strategies present within the Kanjera assemblage reflect varying levels of reduction intensity. This has been shown to be possible based on controlled experiments by least effort experiments by Toth (1982) and later by Moore and Perston (2016), and Potts (1992) suggested that this may be the case with cores at Olduvai Gorge. This study has explicitly tested for this by directly estimating the amount of mass lost from each core in the assemblage. We find that the various core exploitation strategies present at Kanjera South are correlated with reduction intensity – i.e. unifacial cores being the least reduced and multifacial cores being the most reduced. This provides further evidence that various diachritic models of exploitation may not be intentionally applied.

These results also have broader implications for how techno-economic variation arises in the Oldowan record. Variability in the Oldowan record is often interpreted through a socio-cognitive lens, in which technological differences between assemblages are argued to reflect socially learned information, that particularize various groups or individuals (Delagnes and Roche, 2005; Roche et al., 2009, 2018; Stout, 2011). More recently, these criteria have been used to argue for the presence of copying social learning mechanisms in the earliest Oldowan (Stout et al., 2019). However, the results of this work strongly link the application of various technical strategies with the broader land-use system in which tool-use is incorporated. Moreover, the fact that core reduction intensity seems to increase as cores become more rotated further suggests that unifacial, bifacial and multifacial cores may not reflect discrete strategies but are rather points on continuum of reduction that arise out of a need to maximize the utility of high-quality materials.

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 availability 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., 2016, 2017). 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 (Fig. 1). Rather, studies should examine the Oldowan within the broader socio-ecological system. It may be the interaction between function, ecology and sociality that provides information on the cultural capacity of Oldowan tool makers.

# 4.4. Implications for the Oldowan as a whole

The site of Kanjera South is unique in relation to other Oldowan sites of a similar age or older, many of which are situated in close proximity to raw materials sources and are comprised of a singular reduction strategy (Roche et al., 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. This provides us with the unique opportunity to more thoroughly examine how early Oldowan hominins circulated stone across space. 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 may be little incentive to exhaustively reduce a core when material is so abundant (Clark and Barton, 2017). In this sense, the broad scale the technological diversity represented at Kanjera South may reflect adaptations to the specific contextual conditions at this locale.

# 5. Conclusion

Despite the superficial simplicity of the Oldowan, its variability reflects a complex interconnection of ecological, behavioral and social factors. The combination of quantitative measures of stone tool reduction with qualitative characterizations of lithic technology (e.g. Braun et al., 2009; Plummer and Bishop, 2016) provides new insights into the ecological factors that influence Oldowan technology, and hominin behavior.

At Kanjera South, exotic materials are more substantially reduced than local materials, reflecting differences in the quality of the lithologies available. The durability and hardness of exotic materials (Braun et al., 2009a) would have incentivized their transport over longer distances. Differences in reduction 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 suggest that exotic materials were often utilized prior to their arrival at Kanjera South. Although exotic materials are more reduced than local materials, the variance in the amount of stone tool reduction does not adhere to neutral expectations. This result suggests that the lithic assemblage at Kanjera South reflects a structured land-use pattern where hominins may have directed their movement, at least on occasion, 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. Future studies should utilize an integrated approach to understand the behavioral significance of the Oldowan.

# References