## Title

The environmental context of the Middle-to-Late Stone Age Transition in eastern Africa: seasonality as a key factor

## Authors

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## Abstract (max 200 words)

In the transition between the Middle Stone Age (MSA) and the Late Stone Age (LSA) in eastern Africa, the archaeological record shows a gradual and asynchronous decline in MSA features and an increase in LSA characteristics. A link between this pattern and climatic variations has not yet been tested in the region using lithic attribute analysis.

To investigate that, we integrated technological data of blades and bladelets from eastern African contexts (Marine Isotope Stages 5–1) with large-scale paleoclimatic reconstructions. A principal component analysis (PCA) finds the first component (reflecting artifacts' dimensions) significantly correlating with time. This highlights a progressive reduction in size over time, a trend that has already been suggested for the MSA-LSA transition. The second principal component reflects artifact shape and shows a significant correlation with seasonality.

Based on this, we propose that more variable blades reflect greater versatility in foraging strategies as adaptation to unpredictable environments. On the other hand, during periods of mild seasonal change, a more standardized toolkit with thinner, longer elements would emerge from refining and adapting to familiar situations and challenges.

## Introduction

Technological changes in lithic productions are often used to identify cultural shifts in prehistory (especially for the Paleolithic). But the reasons behind technical and cultural transitions are highly debated, mostly because we know how tools change but we lack insight into the underlying reasons.

Such transitions do not always occur synchronously in different regions [1], and they may have a strong regional pattern, which complicates the definition of models for human groups' behavior, adaptation, and evolution [2–4].

The transition from the Middle Stone Age (MSA) to the Late Stone Age (LSA) in Africa is an example of this problem that received considerable attention. It has been linked to changes in material culture, suggesting an increase in cultural complexity; and for a long time, the onset of the LSA in Africa was chronologically associated with the beginning of behavioral

modernity. This was mostly based on what was suggested for Europe: the 'revolutionary' transition from the Middle to the Upper Paleolithic was linked to the distinction between *Homo sapiens* (i.e., "modern" humans) from Neanderthals [5–11]. This generated a confusing superposition between the definition of the MSA-LSA transition and the beginning of "modern" human behavior [5]. However, current evidence shows that the boundary between the MSA and the LSA is not abrupt, and it is now widely accepted that this transition is more of a gradual process than a sudden "revolution" marking the shift to a more "complex" behavior [3,12]. Now, the link between behavioral complexity and LSA-makers is considered obsolete, and the archaeological evidence shows an asynchronous presence and duration of innovations across the African continent [12]. In fact, evidence of what is defined as "behavioral complexity" is present in Africa as far back as >100 ka [13–15], in a fully "MSA environment", and even earlier [16]. Moreover, evidence for great regional variation in late MSA and early LSA assemblages suggests that there were multiple local or regional transitions, each with their specific expression[17]. In eastern Africa, such processes happened in the Late Pleistocene, between ~70 and 15 ka, i.e. Marine Isotope Stages (MIS) 4-2 [2,4,18–20].

The MSA, by definition, is characterized by the presence of the Levallois and discoid methods, as well as retouched and unretouched points (considered the hallmarks of formal MSA tools) [21]. Its chronological range spans from ~300 to 30 ka [3,12,16]. The emergence of the MSA can be considered contemporaneous to the emergence of the first *Homo sapiens* [22,23], but some of traits considered typical of the MSA are occasionally found in Holocene contexts e.g. the presence of the Levallois method for flake production [19,24–27]. In contrast, the LSA is characterized by - depending on the regions - all or some of the following features: (a) increased production of blades and bladelets using volumetric reduction methods, (b) more frequent use of the bipolar technique on anvil (e.g. for the production of unretouched bladelets, or quartz flakes/bladelets to be transformed into microliths), (c) increase in the production of microliths and backed tools, (d) more frequent use of ochre and other ornamental objects (e.g. shell beads), and (e) preference for fine-grained raw materials [2,4,20,28–32].

The asynchronous emergence of the LSA across the African continent offers a great opportunity to investigate the drivers behind these changes, but until now several challenges have prevented a unified view of their mode and tempo [2,12,17].

First, the general models of Late Pleistocene archaeology in eastern Africa have been elaborated mainly on the analysis of single contexts, making it extremely difficult to develop a broader contextualization of the changes observed between MIS 4 and 2.

Moreover, the research is strongly biased toward specific parts of the continent, both because of long-standing research traditions and practical challenges (e.g. political instabilities).

Also, the lack of long-stratified and well-dated sites providing a comprehensive view of the events between ~80 and 17 ka makes it extremely difficult to explore the origin and nature of the transition at a broader scale. For example, in Panga ya Saidi, Kenya, between the layers attributed to MSA and LSA there is an increase in small-sized lithic productions and a selection of finest-grained raw materials in the latter [20,31,33,34]. However, in Nasera, Tanzania, along with the technical changes, it has been proposed that environmental fluctuations may have led to population growth and decreased residential mobility, with no evidence for a particular selection of different raw materials from the MSA to the LSA [32]. However, in these multi-layered archaeological contexts, such patterns do not display a regional tendency and have been recognized exclusively when compared to the MSA levels in single-layer contexts. This has led to an incomparability of the data, challenging the validity of explanatory models at a large scale for the MSA-LSA transition.

The analysis of material culture details human choices, but more is needed to identify the drivers behind them. To do so, it is necessary to look at large-scale human behavioral dynamics, performing large-scale comparative analyses on lithic assemblages and integrating different data (i.e. environmental, genetic, climatic)[35]. One possible explanation to the observed pattern in the LSA-MSA transition is that the emergence of LSA toolkit (e.g. microliths and backed pieces) could be a response to changes in the environmental conditions during the Late Pleistocene [2,4,30,32]. Such hypothesis can only be tested, integrating archaeological and paleoclimatic data[36].

Environmental conditions, including temperature, precipitation, and the differential availability of natural resources, are likely to have played an important role in shaping how past societies behaved and adapted through time. For example, refugia, physical barriers, and corridors led to population bottlenecks and expansions and have driven the emergence, development, and spread of past human behaviors and cultures [37–40].

Eastern Africa is particularly suitable for integrating archaeological and paleoclimatic data, as it includes various habitats that might explain distinct regional traditions in lithic productions [40]. In eastern Africa the climate is mostly arid between MIS 4 and MIS 1 but includes significant oscillations and humid episodes within MIS 4 and 3 [41]. MIS 2 is marked by the so-called "Big Dry" occurring around ~23-20 ka and roughly corresponding to the Last Glacial Maximum (LGM). Humid conditions are observed both before and after the LGM, i.e., before ~24 ka and after ~15 ka [42]. During MIS 1 we have evidence of the African Humid Period (AHP), characterized by increased precipitation in eastern Africa and improved environmental conditions, resulting in a more humid environment[42,43].

At a local level, the sub-region of the Horn of Africa is characterized by aridity during MIS 4, with wetter intervals. During MIS 3, a more humid phase occurred, especially ~50-40 ka, with some arid intervals. MIS 2 in the Horn is characterized by episodes of aridity, with peaks (not always corresponding to the LGM) in which precipitation decreased to up to 25% [42–45]. The region also experienced the impacts of Heinrich Event 1 (around 16 ka), a period of significant cooling and aridification due to massive icebergs breaking off from glaciers in the North Atlantic [41,46]. This event further intensified arid conditions in eastern Africa, contributing to the drying up of key water bodies like Lake Victoria and Lake Tana. [2]Finally, the beginning of the AHP, which is a general wet phase, in the Horn was delayed by the Heinrich event, which prolonged the aridity until around 12 ka [41,42].

Different technological changes in lithic productions are observed during these fluctuations. Among them, a gradual increase of different technical traditions (especially between the end of MIS 3 and the onset of the MIS 2) in the Horn of Africa[2,17], while in Kenya this phenomenon is placed earlier in time [20,31]. As technical changes happened variably in space and time, it is not clear whether the transition from the MSA to the LSA reflects cultural and behavioral

adaptations to large-scale climatic and environmental changes, or responses to localized events that spread to larger areas.

Integrating different data (i.e., lithic attributes and paleoclimate) has already given interesting results, showing a complex scenario for human occupation and dispersal dynamics in North Africa during the MIS 5 [47]. Similar approaches have been proposed for eastern African contexts, but lacking information about the technological process of lithic artifacts production [48]. It is most likely that the MSA-LSA transition was linked to a variety of factors (e.g. large- and small-scale climatic fluctuations, changes in demographic patterns).

In this article we test if and how paleoclimate influenced the technological changes observed during the final MSA and the onset of LSA in eastern Africa.

## Results

*Data analyzed*

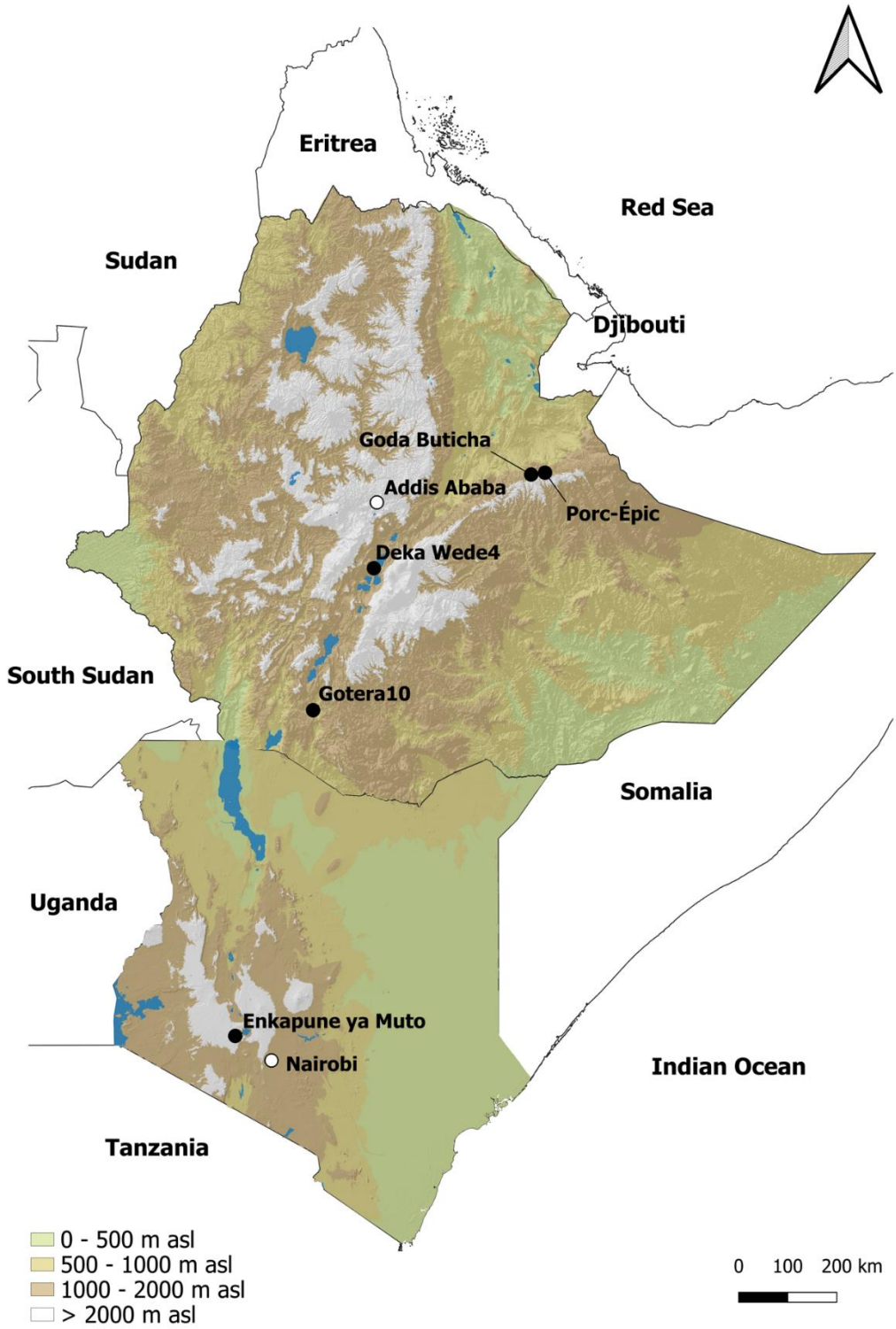


Figure 1: map showing archaeological context considered. 1: Porc Epic; 2: Goda Buticha; 3: Deka Wede4; 4: Gotera; 5: Enkapune ya Muto. Map created with QGIS 3.34.11.

We considered the lithic assemblages from each dated layer of five archaeological sites dated between MIS 5 and MIS 1 in Ethiopia – Goda Buticha (GB), Porc Épic (PE), Gotera 10 (GOT-10), Deka Wede 4 (DW4) – and Southern Kenya – Enkapune ya Muto (EYM) [19,28,49–52] (Figure 1, table 1 and Materials). We focused the analyses on blades and bladelets (flakes in which the length is at least twice the width, also defined "elongated blanks") because 1) their increased presence in the LSA has been used to define the transition[4,53,54] and 2) they are the lithic category for which the most data were found.

| ***Site*** | ***Layer*** | ***Chronology (years BP)*** | ***Cultural Phase*** | ***Sample size*** | ***Number in Figure 2*** |
|---|---|---|---|---|---|
| ***Goda Buticha*** | IIdIIf (030-000) | 63000±700 | MSA | 14 | 4 |
| ***Goda Buticha*** | IIdIIf (100-030) | 44323±2084 - 31893±405 | MSA | 131 | 5 |
| ***Goda Buticha*** | IIc (160-100) | 8000 - 6900 ±0.7 | Middle Holocene LSA | 186 | 10 |
| ***Goda Buticha*** | I (190-160) | 2726±144 - 700 ±100 | Late Holocene LSA | 35 | 11 |
| ***Porc Epic*** | IIId-IIIc | 130000 - 60000 | MSA | 92 | 1 |
| ***Porc Epic*** | IIIb-IIIa | 130000 - 60000 | MSA | 167 | 3 |
| ***Porc Epic*** | II | 130000 - 60000 | MSA | 29 | 2 |
| ***Gotera 10*** | SU6 - SU7 | 45760±540 - 43270±390 | LMSA | 48 | 6 |
| ***Deka Weke 4*** | 1500 | 29 120 ± 160 | LMSA | 102 | 7 |
| ***Enkapune ya Muto*** | GG1.2-3-4-5-7 | 55000 – 45000 | LSA | 46 | 8 |
| ***Enkapune ya Muto*** | DBL1 | 39000±1600 | LSA | 126 | 9 |

Table 1: list of sites considered in the analysis with the identification of chronology, cultural attribution and number of elongated blanks sampled.

## *Morphological trends*

For each elongated blank we collected lithic attributes (e.g. metrics about their shape and size) suitable to compare different collections [55] (see Methods and table 1)

We first performed a Principal Component Analysis (PCA) to evaluate the differences between the MSA and the LSA assemblages (Figure 2: A). In the PCA, the two first principal components accounted for 68.3% of the overall variance. PC1 is mostly influenced by dimensions: maximum length (XTL), maximum width (XTB), and maximum thickness (XT). On the other hand, PC2 is driven by the elongation index (EI) and flattening index (FI). Following this, variation along PC1 reflects changes in size, with smaller blades and bladelets on the left of the plot, and larger ones on the right. Similarly, the value of PC2 captures the shape, with longer blanks on bottom and shorter ones on the top of the PCA (Figure 2).

To better visualize the distribution of lithic assemblages within the PCA space, we summarized the information for each archaeological layer by calculating their centroids: i.e. the average position of all their artifacts (Figure 2: B, Methods). The centroids show a progressive size reduction through time (Figure 2: B). The MSA assemblages (Porc Épic IIIa-d and II layers, Goda Buticha IIdIIf 030-000 (63ka) and IIdIIf 100-030 (~44-31ka) layers, (Figure 1: B nr 1-5) have the largest size. In contrast, Gotera (SU6 and 7, ~45ka) and Deka Wede4 (SU1500, ~30ka) appear on the left side of the graph with smaller artifacts (Figure 1: B, nr 6 and 7). The GG1 layer of Enkapune ya Muto (Figure 2: B, nr 8), dated to ~50 ka tends to be smaller than the Late Middle Stone Age (LMSA) artifacts from Gotera, but bigger that Deka Wede4, even if it is defined as LSA. Enkapune ya Muto DBL lithics (~39ka) (Figure 1: B, nr 9) are smaller than MSA and LMSA ones (as well as GG1 LSA assemblage), but bigger than the Holocene data from Goda Buticha (layers IIc ~8ka and I ~2-0.7ka) (nr. 10 and 11 in figure 2: B). It must be noted that the superimposition of these data in the PCA reflects the blurry boundaries between the LMSA and the beginning of the LSA in the region in terms of blade/bladelet dimensions. It is also worth to highlight the importance of variability between different research traditions and classification of lithic assemblages: the difficulty in distinguishing LMSA from early LSA may also be due to this.

Despite the classification of MSA and LSA for these specific assemblages, the Enkapune ya Muto level dated to ~50ka and defined as LSA, in the PCA (Figure 2: B, nr 8) is an outlier compared to the other LSA cultural phases. However, when comparing the technological changes with the chronology, its position in the plot seems consistent, beyond its cultural attribution (as confirmed by the correlation between PC1 and time).

The PC1 in our results clearly distinguishes between the MSA, LMSA, LSA and Middle-Late Holocene LSA data showing a progressive reduction in size from ~130 ka to the Holocene.

The distribution along PC2 shows a different pattern. In Figure 2: A, both the MSA and LMSA assemblages (purple and olive-green dots, respectively) exhibit a very large morphological variability. Among them, LMSA tends to have more elongated and thinner blades and bladelets, while the MSA has shorter and thicker ones. On the other hand, in figure 2: A, LSA assemblages (in green, while Holocene LSA in blue and red) appear much more homogeneous, with a tendency to have similarly thin and elongated blanks, with LSA at the

lower corner of the graph. The Holocene LSA layers are also characterized by an increase in retouched elongated blanks, indicating a greater presence of backed microliths, geometrics, and retouched bladelets (especially in the Late Holocene LSA layers of Goda Buticha). This reflects another trend beyond a simple reduction in sizes[2,19].

The middle and late Holocene LSA Goda Buticha IIc layer (Figure 2: B, nr 10 and 11) represent an exception to the trend described above, probably due to the co-occurrence of both MSA and LSA characteristics [19]. These results prompted to investigate in more depth the reason behind these patterns.

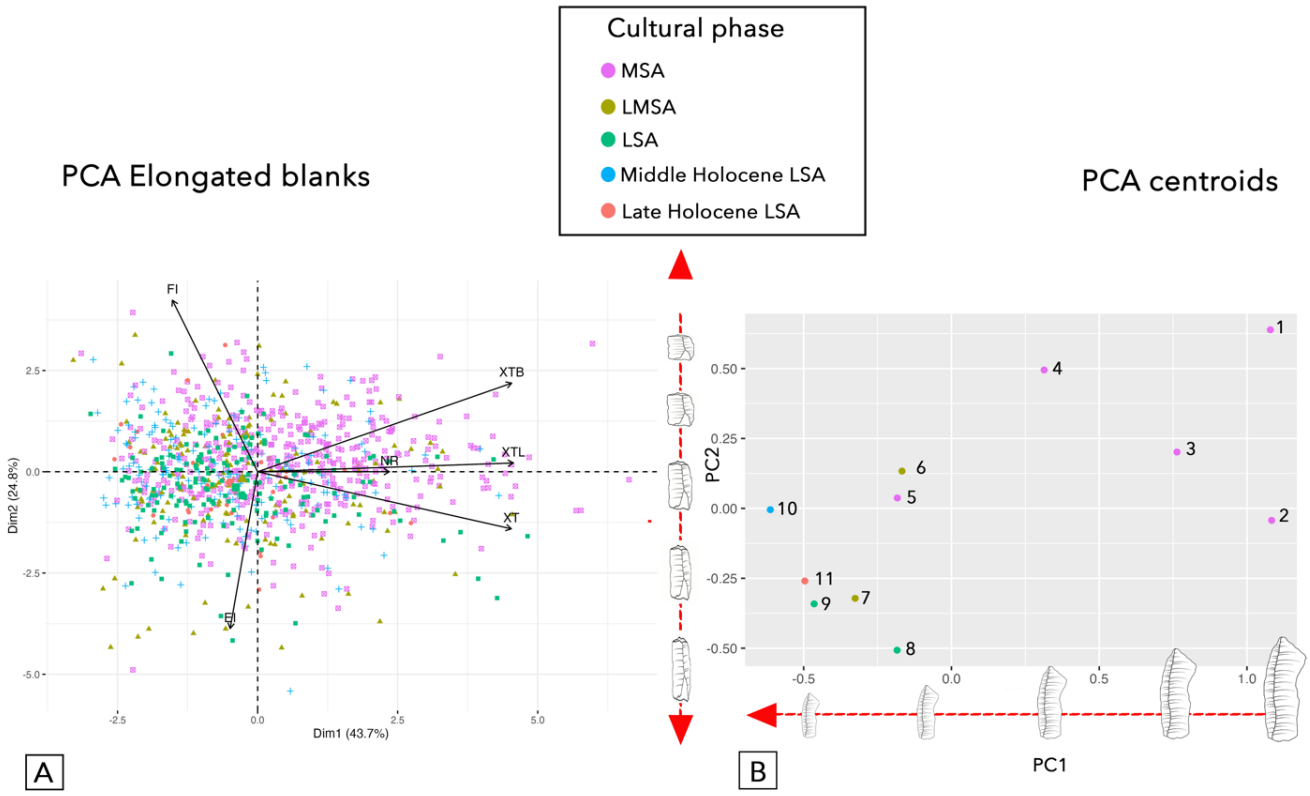


Figure 2: A: biplot with PCA results grouped by cultural phases and showing both individuals and variables; B: PCA showing centroids grouped by cultural phase. Cultural phases: Middle Stone Age (MSA), Late Middle Stone Age (LMSA), Late Stone Age (LSA), Middle Holocene LSA and Late Holocene LSA. Numbers indicate each individual archaeological layers. MSA: 1: Porc Epic IIId-IIIc; 2: Porc Epic II; 3: Porc Epic IIIb-IIIa ; 4: Goda Buticha IIdIIf (63ka); 5: Goda Buticha IIdIIf (44-31 ka). LMSA: 6: Gotera 10; 7: Deka Wede 4. LSA: 8: Enkapune ya Muto GG1; 9: Enkapune ya Muto DBL1. Middle Holocene LSA: 10: Goda Buticha. Late Holocene LSA: 11: Goda Buticha.

*Raw material selection as potential driver of changes*

Raw material selection is among the most common drivers behind technological changes[20,33,56–58]. Therefore, we tested if different raw materials affected the shape or size of the analyzed assemblages.

There is evidence of several sources for the materials utilized within our sites (see Materials and Methods).

Similarly to what we did above, we calculated for each assemblage the centroids for the different raw materials over the first two principal components (Figure 3: A).

The average artifact sizes of obsidian, chert, and quartz artifacts follow the expectations for their chronology and cultural phases: larger during the MSA and show a progressive reduction in later phases (Figure 3: B).

However, raw materials such as basalt do not display a consistent pattern of size reduction in relation to chronology: some large basalt artifacts are attributed to the Holocene LSA or other cultural phases (Figure 3: B). This homogenous use of the different raw materials over time supports the idea that it is not the choice of materials the driver of the technological trends observed in our data,

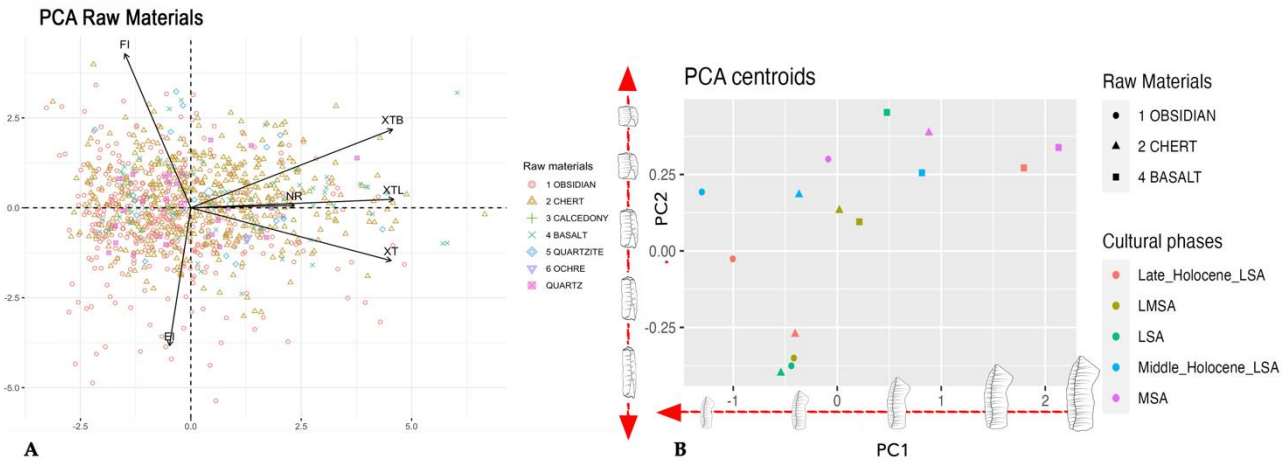


Figure 3: PCA showing each elongated blanks and variables subdivided by raw materials. Variables used for the PCA are elongation index (EI), flattening index (FI), Maximum breadth (XTB), maximum length (XTL), maximum thickness (XT) and number of dorsal scars (NR). (A). Plot showing the distribution of PC raw material centroids indicating also cultural phases (B).

*Palaeoclimate as potential driver of changes*

We then tested the hypothesis of paleoclimate as a potential driver for the technological changes observed in our data. We linked each assemblage to palaeoclimatic variables reconstructed at a large scale [56] for its location and age using the *pastclim* package [57] in R. The seasonality of resource acquisition has been recognized as a key aspect of hunter-gatherer subsistence behavior as well as social and economic organization [58]. For this reason, we focused on climatic variables that emphasize the difference between seasons, i.e. temperature annual range (the difference between the maximum and minimum temperatures of the year), and precipitation seasonality.

Because of the large chronological uncertainty of some of the layers, we did not use mean/median ages. Instead, for the whole list of layers, we resampled 1000 times a set of dates from each relevant range [59]. For each of these 1000 sets of resampled dates, we calculated the Spearman's correlation between the positions of the centroids of each layer on PC1 and PC2 and three factors: time, temperature annual range, and precipitation seasonality (Figure 4). As an aggregated measure of correlation, we used the mean r over all resampled sets, and we calculated the significance as the number of them in which the p-value was below 0.05[59].

As already suggested by Figure 2: B, PC1 is significantly correlated with time (Figure 4: A), even after the chronological resampling (mean r=-0.83, all resampled sets significant). PC2 shows a significant correlation with both measures of seasonality: temperature annual range (mean r=-0.69, around 3/4 of the resampled sets significant; Figure 4: D) and precipitation seasonality (mean r=-0.69, more than 2/3 of resampled sets significant; Figure 4: F). Because temperature annual range and precipitation seasonality are significantly correlated (see methods, figure 6), we cannot disentangle the effect of temperature and precipitation, and from now on we will discuss the results in terms of overall climate seasonality.

Elements with a higher flattening index (i.e. with higher values of PC2) are found in locations with larger differences between seasons, while elements with a higher elongation index (lower values of PC2) are associated to a climate that is more uniform over the year.

To check if the impact of seasonality we observe is linked to large-scale fluctuations in precipitation and temperature, we also tested correlation for either PC1 or PC2 mean annual temperature and total annual precipitation, but the results are not significant (Methods, Figure 5).

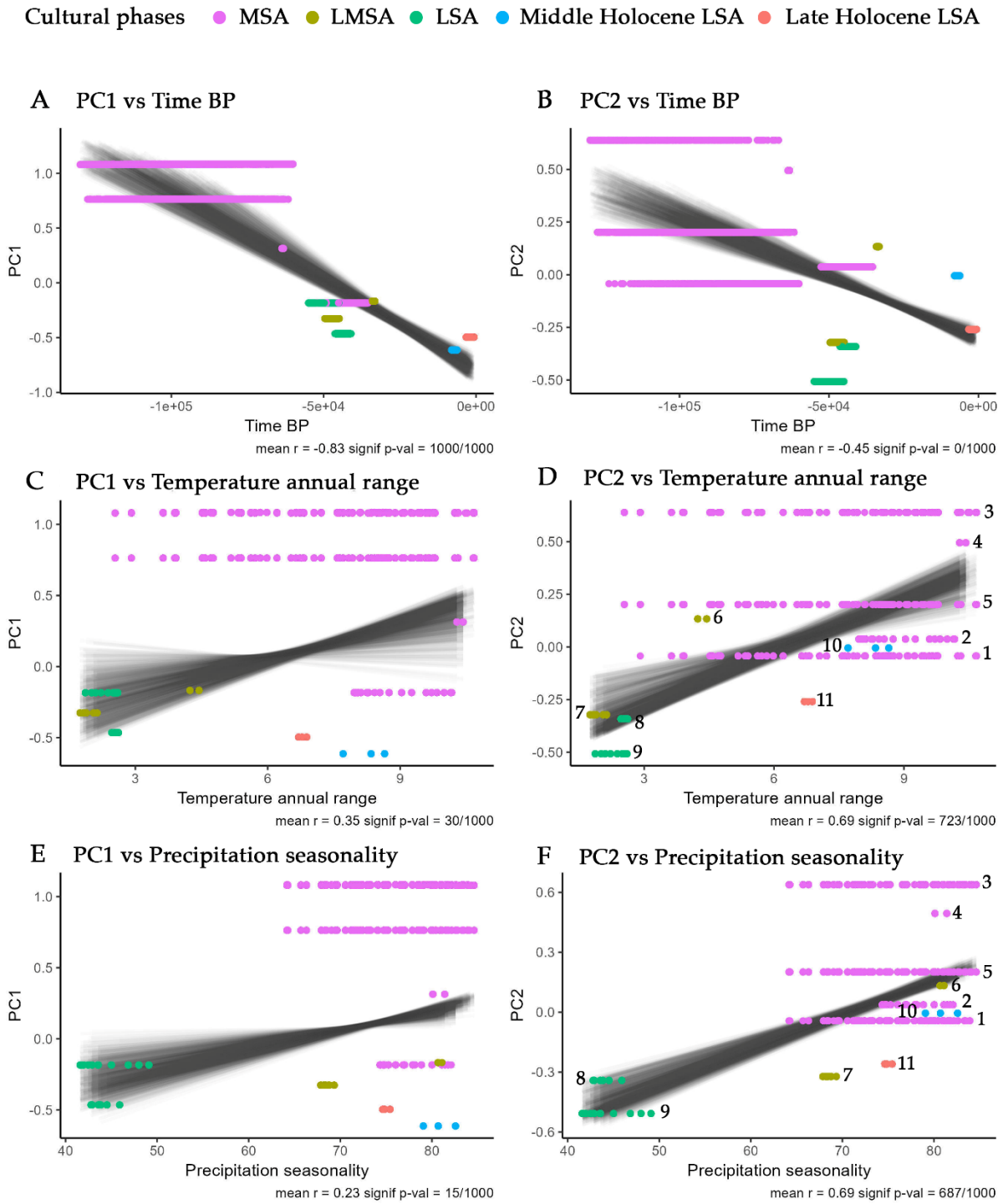


Figure 4: Integration of palaeoclimate data to test the role of climate and environment within the MSA/LSA transition. Box A shows the correlation between PC1 and the chronology, while box B shows PC2 and chronology. Box C and D shows the correlation between PC1 and 2 and temperature annual range. Boxes E and F show the correlation between PC1 and 2 and precipitation seasonality. The p-

values show a significant correlation between PC1 and time, and PC2 and temperature annual range. Numbers in boxes D and F indicate each individual archaeological layers. MSA: 1: Porc Epic IIId-IIIc; 2: Porc Epic II; 3: Porc Epic IIIb-IIIa ; 4: Goda Buticha IIdIIf (63ka); 5: Goda Buticha IIdIIf (44-31 ka). LMSA: 6: Gotera 10; 7: Deka Wede 4. LSA: 8: Enkapune ya Muto GG1; 9: Enkapune ya Muto DBL1. Middle Holocene LSA: 10: Goda Buticha. Late Holocene LSA: 11: Goda Buticha.

## Discussion

While a reduction in size of blanks, cores, and tools in the late Pleistocene has been commonly reported, the reasons behind such choices are highly debated [17,34,60]. As already discussed, size reduction was one of the characteristics that defined the LSA and differentiated it from the MSA [20,29,34,53,60,61] but it is now accepted that small size alone is not enough to categorize an assemblage as LSA [17].

Small-sized artifacts (<30-50 mm) are documented in various contexts, even older than LSAs [60–62]. In eastern Africa, they are found at Omo Kibish ~200ka, Herto dated ~150ka and Aduma, ~80ka, as well as at Panga ya Saidi ~67ka [20,31,34,63,64]. In South Africa, evidence of small flakes and blades is present as early as the MSA, sometimes associated with the Howiesons Poort industry (characterized by small geometric tools used probably as inserts in multi-component tools)[65–67].

Our results show a clear trend toward the reduction in the size of elongated blanks through time; a pattern more evident for assemblages classified as MSA (Figure 2: B). However, if we consider the cultural label classification, the reduction in size started before the MSA/LSA transition and it follows a chronological order that goes beyond the cultural definition. For example, the MSA GG1 layer from Enkapune ya Muto (8 in figure 2: B), has on average bigger blades and bladelets than the LMSA assemblage of Daka Wede 4, similarly to Gotera 10.

In summary, our results show a clear trend of progressive size reduction in both blades and bladelets through time within the contexts spanning from the MSA to the Holocene LSA. On the other hand, the incoherency between the definition of MSA-LSA transition and such size changes should push us to consider this phenomenon as something not marking the transition itself, but more of a chronological trend.

Various hypotheses have been proposed regarding the shifts in artifact sizes, accompanied by ethnographic analyses in contexts from both North America and Australia [60,68],including

symbolic aspects related to the miniaturization of flakes and blanks in general [34,68]. Additionally, they consider factors associated with raw material economics in the contexts of population growth, reduced residential mobility, and the cost-benefit strategy of producing a greater number of smaller tools to maximize efficiency[60,62,68]. In many contexts, raw material selection played a significant role in lithic production[69–71] . Pargeter and Shea [60] suggest that some raw materials, (e.g. quartz) are easier to work into smaller-sized artifacts. There is evidence of technological changes in Eastern African industries during the Late Pleistocene and early Holocene being associated to the exploitation of different raw materials [20,31]. The transition from the MSA to the LSA has been suggested to be linked to the selection of finer-grain raw materials, better suited for small tools [20,33]. While this evidence has been tested on single sites [20], our results do not support it on a larger spatiotemporal scale.

As mentioned, extensive discussions have occurred on the ecological and environmental aspects of lithic miniaturization and, in general, technological changes in stone tool use and production [28,62,68,72]. In eastern Africa during the Late Pleistocene, a series of environmental changes led to oscillations between arid and humid periods [41]. In our results, the correlation between the shape of blades and bladelets (i.e. elongation and flattening) and seasonality suggests adaptive strategies in response to different levels of resource predictability. The latter has been proposed to have influenced stone tools production and functions in older periods [73,74].

Human response to climatic changes and environmental conditions during the Pleistocene is reflected in their ability to adapt and live in different ecologies while habitats expand or shrink. The diversity in lithic production and the different outcomes of technical evolution within these groups likely result from a modification and/or adaptation of hunting, butchering, animal processing strategies, and other subsistence practices based on the surrounding environment. It is widely accepted that resources predictability (a consequence of more stable environments) has impacted hunter-gatherers behavioral dynamics, in terms of subsistence, settlement, and mobility strategies [58,75–77]. For example, the exploitation of raw materials to anticipate inadequate conditions is proposed as one of the features that differentiates the concept of curation (intentional maintenance, reuse, and prolonged use-

life of stone objects) from the one of expediency (minimal technological effort in object production) [77]. Going beyond the multiple definitions of these concepts [78–83], it was proposed that curated objects are produced where the need to cope with unpredictable environmental conditions leads to an anticipated preparation of raw materials. Objects were curated because there was no guarantee of always having the necessary raw materials available, in this way time was invested in advance [84–86]. Conversely, in favorable conditions, this anticipation may have been not necessary, with no time invested in advance, with expediency reflecting highly predictable resource availability [58,82,86].

Similarly, for our results, we hypothesize that in periods of mild seasonal variations, the prevalence of longer and thinner elongated blanks could be linked to predictable resource availability. In regions with relatively stable environmental conditions, we expect that animal (and vegetable) resources would be available for the whole year. In such a scenario, hunter-gatherer groups would have the opportunity to rely on a stable toolkit for activities such as hunting and fishing, which would require homogeneous, longer and thinner blades [77,78,80].

On the other hand, a preference for more variable, shorter, and thicker blades may be a response to an environment where resource availability is relatively unpredictable. In such environments, hunter-gatherer groups would be less specialized in their hunting or foraging strategies, and more versatile to cope with the unpredictable fluctuations in food resources. Thicker blades can be used for a larger set of activities [58,77,79,80].

The analysis reveals that the levels characterized by longer and thinner blades and bladelets, in descending order, are GG1 from Enkapune ya Muto, DBL from Enkapune ya Muto, Deka Wede4, the Middle Holocene levels of Goda Buticha, those dated between 44–31 ka at Goda Buticha, and Gotera. In GG1, retouched tools prominently include large, backed segments, indicating a focus on robust tool forms, which are more abundant compared to those in the DBL1 assemblage. In DBL1, retouched tools are rare, consisting of end-scrapers, scaled pieces, and a few geometric microliths, reflecting minimal retouching activity[50,53]. The Deka Wede4 assemblage also features sparse retouched tools, including convergent sidescrapers, unifacial points, and end-scrapers. Some blanks display inverse proximal thinning retouch, but most artifacts were likely used without further modification[19,49].

In the Late Holocene levels of Goda Buticha, retouched tools mainly consist of microliths, particularly backed microliths and retouched bladelets, predominantly made from obsidian. This indicates a strong preference for elongated blanks, with minimal point production. The Middle Holocene levels of Goda Buticha (Layer IIc) are characterized by retouched tools primarily made on blades and bladelets, especially from obsidian. These include unifacial and bifacial points with invasive retouch, as well as geometric microliths, such as crescents. In the Early Holocene levels of Goda Buticha (IId-IIf), retouched tools emphasize elongated blanks, particularly retouched blades made from obsidian. Points, including unifacial and bifacial types, are significant and exhibit invasive retouch. However, only two microliths are present (one backed microlith and one retouched bladelet), indicating a lower emphasis on microliths.

At Gotera, only a small portion of the lithic assemblage is retouched, consisting mainly of notches and denticulates on blade and bladelet supports, primarily made of quartz[87,88].

Our analyses highlight the need to explore all aspects related to the interpretation of an archaeological context: not only how objects were produced, i.e. technology, but also mobility, duration of occupations, and object function. Integrating all available data (e.g. functional and residue data on lithics, geomorphological and spatial data, site formation processes, faunal data, isotopic analysis for human and animal mobility, etc.) from archaeological excavations can significantly deepen the interpretation of past human behaviors [35].

For example, functional analysis of lithics is still underperformed in African prehistory, where surface lithic assemblages are more frequent than from stratigraphic deposits. In some southern African contexts, use-wear and residue analyses explored technological adaptation of humans during the MSA, and hunting strategies and hafting methods [89,90].

Our results show the advantages of data integration and comparative analyses of lithic attributes to test general models built on the interpretation of individual sites to pursuit this aim, there is an increasing necessity to standardize data collection for lithic industries and to establish a list of essential attributes to record for each assemblage. This standardization may facilitate the comparison not only for morphometric attributes but also technological traits, including reduction methods, techniques, etc.

Lastly, we still need to be cautious with the combination and use of archaeological data for large comparative analyses, especially when manipulating data on lithic technologies. We need a very deep understanding of these materials, the way they have been produced and the implications that technologies had for the reconstruction of past human behavior.

Our research represents the first case study in which the sites under consideration have been integrated into a large-scale approach based on the analysis of lithic assemblage attributes. However, despite the results obtained, it is important to emphasize the need to incorporate more contexts within this model, following the same methodological approach, to achieve a large-scale understanding of the MSA-LSA transition in eastern Africa. In particular, it is necessary to mention several contexts that fall within this chronological range and would be essential to include in these analyses, to further test these patterns, but are not available at the time of this study. In Ethiopia sites dated to MIS 4 such as Shinfa Metema 1[91]; to the MIS 3 such as Mochena Borago [92,93], Fincha Habera [94]; Gorgora [95]; to the MIS 2 such as Sodicho [96]. In Kenya sites dated to MIS 4 such as Panga ya Saidi [20,31], to the MIS 3 such as Rusinga Island sites [97]; Lukenya Hill [98]. This will allow to explore further results for the human technical behavior between MIS 5 and 1 in eastern Africa.

## Conclusions

Eastern African Late Pleistocene represents an ideal place to test different hypotheses linked to human group behavior, the reasons behind technological changes, and their relationship with climate and environment. The region is characterized by a diversity of environments that generated varied responses to past climatic fluctuations, leading to a differentiation in the behavioral responses of hunter-gatherers [2,4,41,99]. Our study shows a correlation between the shape of elongated blanks (and so, most likely, their use) with seasonality. We propose that during periods with mild seasonal variations, longer and thinner blades and bladelets may be prevalent due to predictable resource availability. Because of the climatic stability animals would have less reasons to migrate, and hunting would have been more predictable, leading to a more uniform toolkit. In contrast, in moments of unpredictable resource availability, shorter and thicker blades and bladelets may have been favored, reflecting a

greater versatility in foraging strategies as well as other activities, to cope with unpredictable environments.

Through the combination of different data, both archaeological and paleoclimatic, with the collaboration of multiple researchers providing the raw data for the analyses, we have shown the importance of this study in explaining phenomena related to the cultural evolution of past human groups. Furthermore, our research highlighted the strong need to establish a mandatory list of attributes to record during analyses of lithic industries, enabling not only data sharing but also their comparison for minimizing errors. Additionally, it is desirable to strengthen the analyses on all aspects of archaeological data, including functional analyses of artifacts to gain a better understanding of the reasons behind some of the major technological changes in the archaeological record.

## Materials and methods

### *Lithic assemblages*

In this article, we have examined elongated unretouched blanks (named blades and bladelets according to the common terminology for lithic categorization, where they are defined as flakes with a length twice or more their width) from five archaeological sites in eastern Africa, spanning stratigraphic sequences from MIS 5 to MIS 1.

One reason for the lack of a clear model on factors driving technological changes in parts of eastern Africa is the limited amount of datable archaeological evidence from this period. On the other hand, there is also a complete lack of a comparative analysis of lithic assemblages that goes beyond the mere typological classification of artifacts, potentially leading to interpretative errors [100].

Based on the above statements, the sample selection for this analysis was based on two specific criteria:

1. **Chronological**; All the earliest MSA contexts (MIS 7-6) or, in general those contexts that are too far in terms of chronology from the approximate date of the MSA-LSA transition

were excluded from the selection. Additionally, to integrate paleoclimatic data, a chronological attribution is needed.

2. **Analytical**. This is a fundamental criterion used to select samples for analysis. As mentioned in the introduction of this chapter, it is crucial to avoid typological comparisons based on the presence/absence of tool types that might exclude information about the production of lithic artifacts. To be included in a statistical methodology that compares technological attributes (both qualitative and quantitative), the collections and datasets must be amenable to a piece-by-piece artifact analysis in which all critical variables can be measured and assessed. It is clear that the technological approach based on the analysis of lithic artifact attributes is not a new methodology, however some assemblages collected and studied many years ago would require a full re-analysis to enable comparable data to be derived.

Based on the above criteria, in order to examine an archaeologically and chronologically significant sample, the sites of Goda Buticha, Porc Epic, Gotera 10, Deka Wede 4 in Ethiopia, and Enkapune ya Muto in Kenya were considered in this analysis.

### *Archaeological sites*

Goda Buticha is a cave in south-eastern Ethiopia with a long stratigraphic sequence divided into two main complexes, II and I. The deposit is dated from the end of MIS 4 to MIS 1, with a chronological gap dated to MIS 2 [19,101]. This site stands out as one of the few well-dated long stratigraphic sequences in Ethiopia [19].

Porc Epic cave, located in south-eastern Ethiopia, exhibits four main stratigraphic units. The lowest units (IV and III) are considered MSA based on the analysis of lithic assemblages; unit II shows a mixed MSA/LSA presence, while unit I is attributed to the LSA [102]. Here only artifacts from the lower units are considered into the analysis. Preliminary results of an OSL dating program of the lower units of Porc-Epic gave ages ranging from MIS 5 to MIS 4 [103,104]. We therefore worked with the hypothesis that the lower assemblages have an age range between 130 and 60 ka. We note that this chronological attribution is earlier than radiocarbon dates on hells available for the site [105,106] but other dates suggested an earlier chronology for the lower levels of Porc-Epic (see review in Assefa et al. [107]).

The Gotera area situated in southern Ethiopia near the Kenyan border has yielded open-air evidence of human occupation associated with MSA technological features [87,108]. The GOT-10 site has provided a stratigraphic sequence dated to MIS 3, including lithics, faunal remains, and evidence of fireplaces [88].

Deka Wede 4, located in the Ziway Sahla basin, is chronologically placed within MIS 3 through correlation with Deka Wede 1 site [52].

Lastly, Enkapune ya Muto, in southern Kenya, has yielded three levels dated to the Late Pleistocene: RBL4 containing MSA materials, GG and OL with LSA materials dating to ~50 ka, and DBL dated around ~40 ka with evidence of a younger LSA [50,53]. Here, only artifacts from GG and DBL layers were considered.

### *Sources of raw materials*

At Gotera, the principal raw materials used are quartz and basalt; they are available within the site, and in the surrounding area [87]. Obsidian sources in Ethiopia are relatively abundant [109]. Analyses conducted on obsidian artifacts from Porc Epic site showed that its source was located ~250 km distant from the site. This evidence shows that this raw material was transported to the site from a very distant location[109]. In Goda Buticha Chert, basalt, and quartzite are assumed to have a local origin, while obsidian, despite its high frequency, lacks a known nearby source[19,110]. There is an obsidian outcrop c. 40 km away from the site, but its use has not been demonstrated [19]. Although in Goda Buticha there is no particular evidence for different raw material selection in the layer IIdIIf, in the IIc and I assemblages obsidian is the mostly used raw material, to produce both retouched tools and elongated blanks (only in GB-I) [19].

Lithic assemblages in Enkapune ya Muto show a few non-local raw materials, but are mainly produced using obsidian from the volcanic area of the central rift, relatively close to the site[28].

### *Data analysis*

Regarding lithic categories (e.g., flakes, elongated flakes, tools, cores, etc.), we specifically chose to focus on unretouched and complete blades and bladelets. The reason is that their presence seems to increase during the LSA [29,49]. Moreover, they are the type of blanks for which the most data were available for the sites of interest, which allows us to increase the chronological and geographical scale of the analysis.

Each lithic in the dataset has been associated with a chronology and a cultural phase. Cultural phases have been attributed in accordance with the publication related to the contexts analyzed. Accordingly, we have identified the Middle Stone Age (MSA) for Porc Epic layers and the Goda Buticha layers dated between 63 and 31 ka; the Late Middle Stone Age (LMSA) for the Gotera 10 and Deka Wede 4 assemblages; the Late Stone Age (LSA) assemblages belong to Enkapune ya Muto show different chronologies which overlaps with some LMSA assemblages, in fact GG1 LSA layer at Enkapune ya Muto is dated ~50 ka, while the DBL1 is dated ~39ka. The Holocene LSA (Middle and Late Holocene LSA) from Goda Buticha, are dated from ~8 ka to 700 years ago (Table 1) [19,49,51,52,87,101,108].

### *Choice of technological attributes for the analyses*

It is important to highlight that information on the lithic assemblages analyzed have been collected by different researchers from various research traditions, each with distinct objectives. This led to great variability in the metrics considered, the categories analyzed, and other technical choices that can highly impact our analyses.

Caution must be given when choosing metrics and technological attributes to compare such different sets of data [55,100]. Following the approach designed by Pargeter and colleagues [55], we focused on specific metrics and technological attributes that are most suitable for statistical analyses of data collected by different individuals or research groups (Table 2). These include technological measurements (maximum length, width, and thickness), the number of dorsal scars, blank completeness, elongated index, and flattening index. We analyzed these attributes from the five different datasets related to the sites mentioned above.

| Variables for elongated blanks | |
|---|---|
| Maximum Length | XTL |
| Maximum Breadth | XTB |
| Maximum thickness | XT |
| Number of Scars | NR |
| Elongation index | EI |
| Flattening index | FI |

Table 2: Variables used for the PCA on elongated blanks.

### *Principal Component Analysis*

We performed Principal Component Analysis on lithic attributes (Table 2) using the *FactoMinerR* package [111] and its *prcomp()* function. Cultural phases and stratigraphic units of each site were chosen as variables for grouping the PCA results and the two principal components. To better visualise how the different cultural phases are located in the PCA space, we computed the centroids for each archaeological layer (Figure 2) and raw material (figure 3) as the mean of PC1 and PC2 of all artifacts included in the respective category.

### *Chronological resampling and paleoclimatic analyses*

Some of the assemblages analyzed (Table 1) show a large chronological uncertainty. Following Will et al 2021 [59] for each assemblage we resampled randomly 1000 times a date from its whole chronological range associated.

We then used the R package *pastclim* [57] to access the palaeoclimatic reconstructions from Krapp et al., 2021 [56]. This dataset includes 18 bioclimatic variables spanning from 800,000 years ago to the present, with time intervals of 1000 years.

We used the "*location_slice()*" function from *pastclim*, to associate each resampled set of dates for the assemblages with the relevant climate variables (i.e. reconstructed for their

spatial coordinates and resampled age). We considered temperature annual range (bio07) and precipitation seasonality (bio15).

We then calculated 1000 times the Spearman's correlation between the values of PC1 and PC2 for each centroid against the resampled time and associated climatic variables for their respective locations. We plotted each individual regression line, and calculated the mean value of r, together with the number of resampled dates for which the p-value was below 0.05 [59].The scatterplots were created using the *smplot2* package[112]. All graphical representations were generated using the *ggplot2* R package [113].

To check if the impact of seasonality is the result to large-scale fluctuations in precipitation and temperature, for correlation between either PC1 or PC2 and mean annual temperature (bio01) and total annual precipitation (bio12), but the results are not significant (Figure 5).

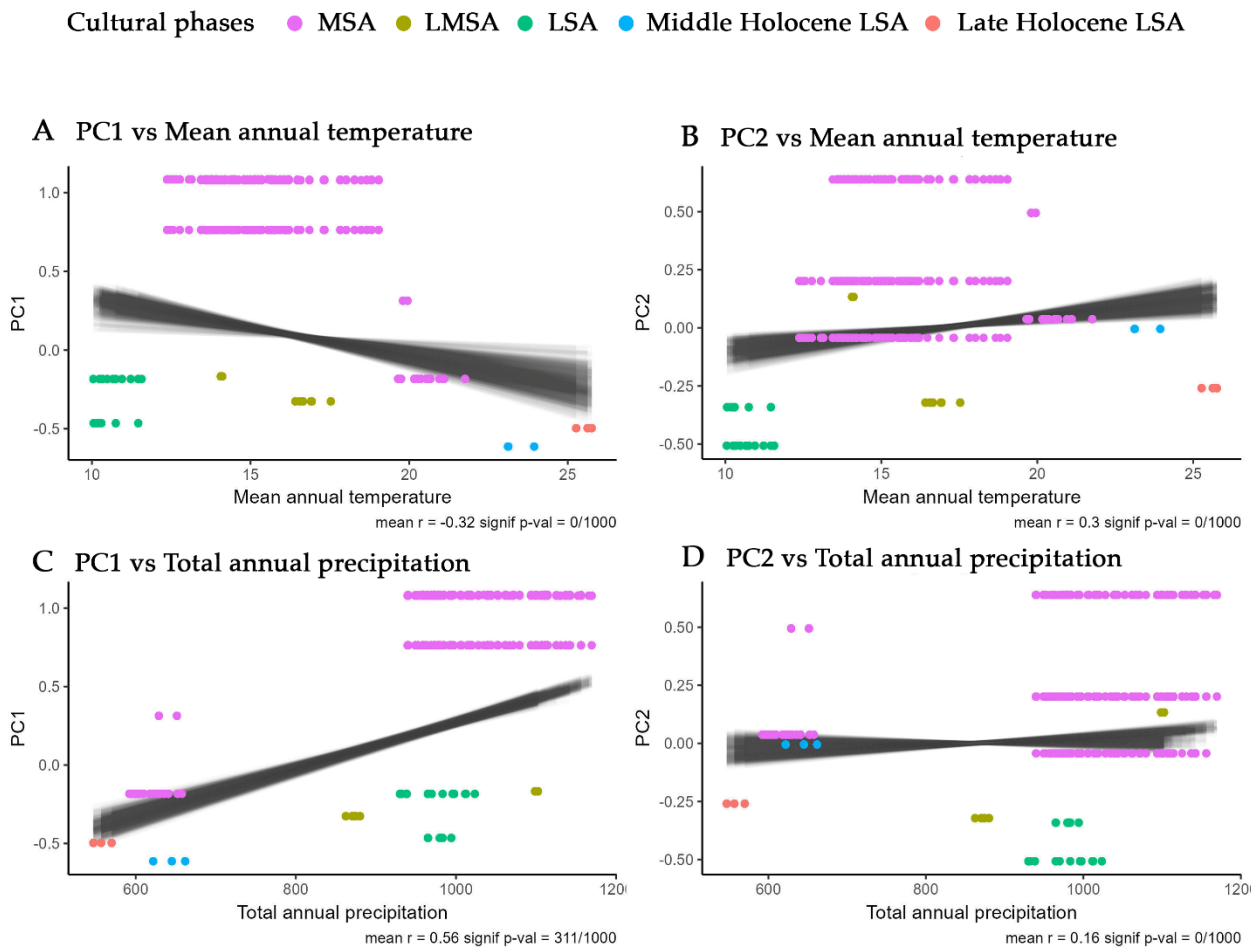


Figure 5: plot showing the non-significant correlation between PC1 and 2 with mean annual temperature (A and B), and PC1 and 2 with total annual precipitation (C and D).

To better interpret our results, we also tested if temperature annual range and precipitation seasonality are significantly correlated and found that they are (Figure 6).

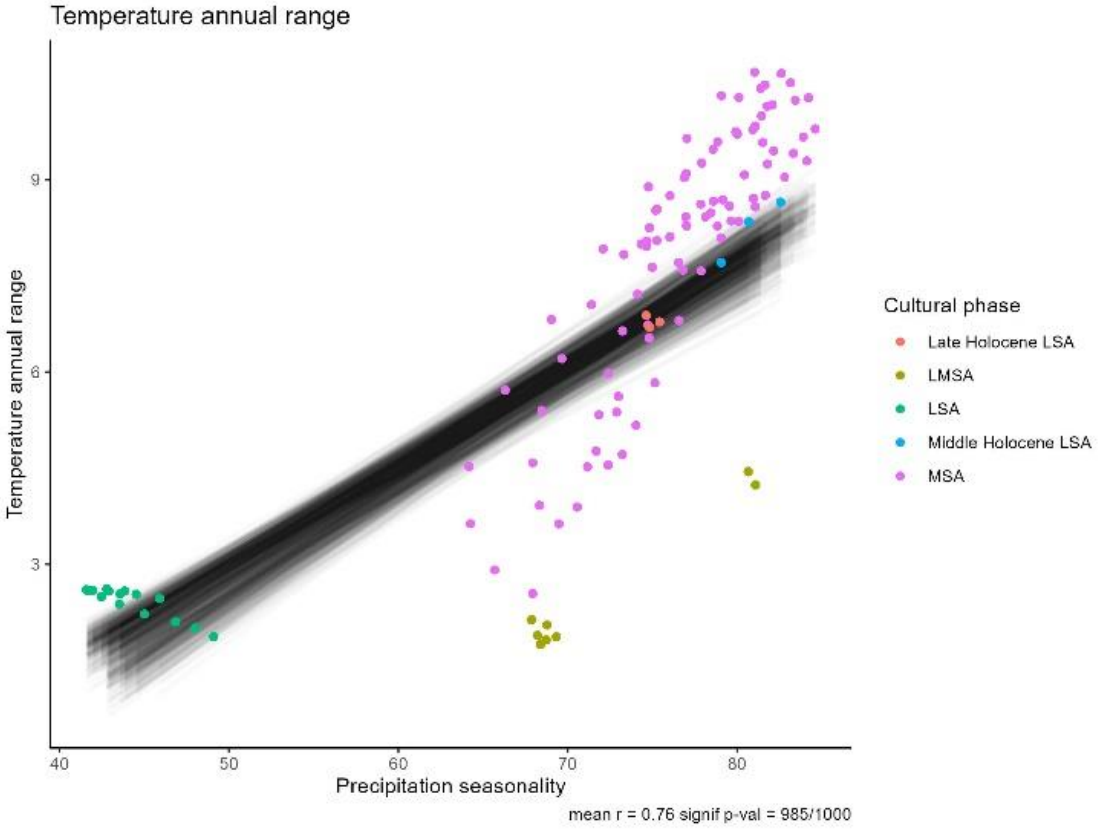


Figure 6: plot showing the significant correlation between temperature annual range (BIO07) and precipitation seasonality.

### *Check for cross-correlation between time and seasonality*

To check for the potential influence of time on our results, we tested for correlation between both variables of seasonality considered (Temperature annual range, bio07 and Precipitation seasonality, bio15) and time. We do not find support for this hypothesis (figure 7): in both cases the level of correlation varies a lot based on the specific age resampling (which points towards no clear effect of time on the variable), the mean values of r are low, and a very small number of age resamplings show a significant correlation (which is in line with it being a random outcome).

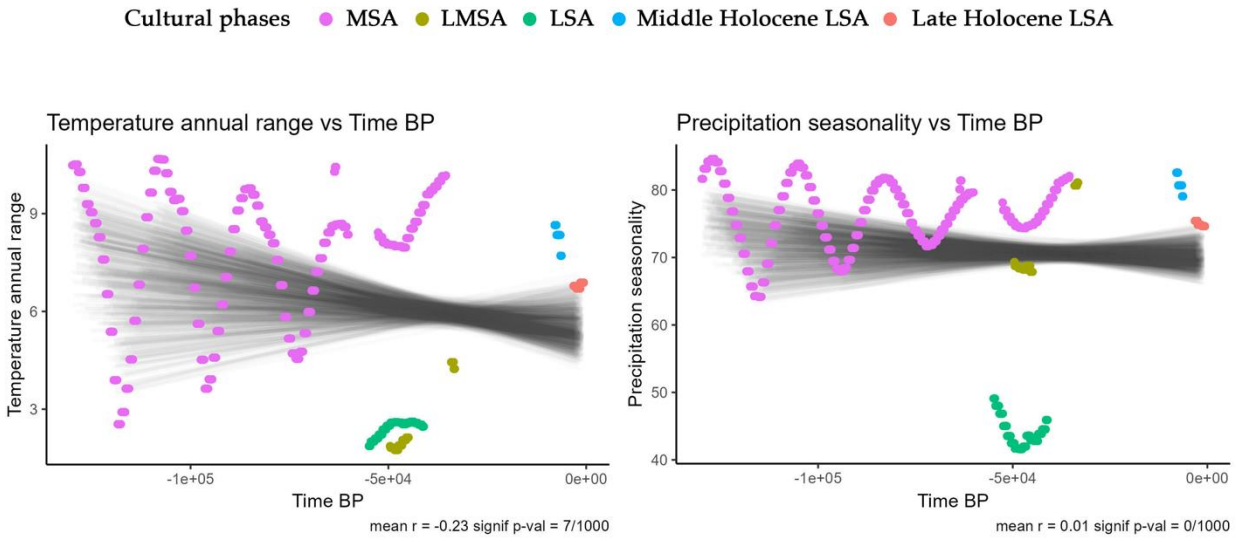


Figure 7: plot showing the non-significant correlation between Temperature annual range and time (left) and precipitation seasonality and time (right).

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## *Author contributions*

AM, ML and MF conceived the study with inputs from EES. MF, BH, AL, CM collected the data. AM and ML defined the methodology. MF performed the analyses and created the figures with inputs from ML and AM. MF, ML, AM and EES provided the interpretation. MF and ML wrote the original manuscript. All authors were involved in reviewing the manuscript. MF and EES obtained the fundings.