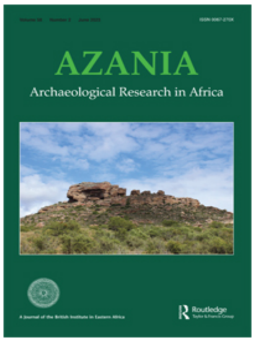

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Stone point variability reveals spatial, chronological and environmental structuring of eastern African Middle Stone Age populations

Lucy Timbrell [a,b*], Behailu Habte [c], Yosef Tefera[c], Christine Maroma[d], Emmanuel Ndiema [d,e], Kimberly Plomp [f], James Blinkhorn [g] and Matt Grove [a]

[a]Department of Archaeology, Classics and Egyptology, University of Liverpool, 12-14 Abercromby Square, Liverpool, L69 7WZ, United Kingdom; [b]Histoire Naturelle de l'Homme Préhistorique, Museum National d'Histoire Naturelle, 57 Rue Cuvier, Paris 75005, France; [c]Ethiopian Heritage Authority, National Museum of Ethiopia, King George VI Street, Addis Ababa, Ethiopia; [d]Department of Archaeology, National Museums of Kenya, Kipande Nairobi, Kenya; [e]Department of Archaeology, Max Planck Institute for Geoanthropology, Kalhaischestraße 10, Jena, 07745, Germany; [f]School of Archaeology, University of the Philippines Diliman, Quezon City, 1101, Philippines; [g]Pan-African Evolution Research Group, Max Planck Institute for Geoanthropology, Kalhaischestraße 10, Jena, 07745, Germany and Centre for Quaternary Research, Department of Geography, Royal Holloway, University of London, Egham, TW20 0EX, United Kingdom

ABSTRACT

Stone points are one of the key features used to define the African Middle Stone Age (MSA). Regional patterns in their shape and size through time have been thought to reflect inter-group interactions and networks of populations and are used to define cultural phases within the MSA. However, eastern Africa does not have distinctive and widely applied chrono-stratigraphic point variants that divide its MSA record, which is often described as being highly variable. This paper presents a metric and geometric morphometric analysis of eastern African MSA points and evaluates potential drivers of variation in them in relation to null models of isolation by distance, time and environment. Approximately half of the shape variance in our sample can be explained by spatial, temporal and environmental differences, as well as by size, indicating a degree of demographic continuity through sustained cultural transmission. A portion of the remaining variance likely represents stylistic differences between assemblages, which are often the subject of interest in archaeological studies. The highly variable nature of the eastern African MSA may reflect the region's refugial positioning within the continent, with point technology a flexible adaptive system that was dynamically employed across Africa during the MSA depending on varying social and ecological contexts, resulting in the appearance of both 'generic' and 'specific' tool forms at particular times and places.

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CONTACT Lucy Timbrell Lucy.Timbrell2@Liverpool.ac.uk
*Present address: Human Palaeosystems Group, Max Planck Institute for Geoanthropology, Kalhaischestraße 10, Jena, 07745, Germany

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RÉSUMÉ
Les pointes de pierre sont l'une des caractéristiques-clé utilisées pour définir l'Âge de Pierre Moyen africain (Middle Stone Age, MSA). Il a été proposé que les distributions régionales dans les forme et les grandeurs au cours du temps reflètent les interactions entre groupes et les réseaux de populations, et ces distributions sont utilisées pour définir les phases culturelles au sein du MSA. Cependant, l'Afrique de l'Est ne possède pas de variantes chrono-stratigraphiques dans les pointes qui soient distinctives et largement appliquées et qui segmentent les données du MSA. Du reste ce registre du MSA est souvent décrit comme étant très variable. Cet article présente une analyse morphométrique métrique et géométrique des pointes MSA d'Afrique de l'Est, et évalue les facteurs potentiels de leur variation par rapport aux modèles nuls d'isolement en fonction de la distance, du temps et de l'environnement. À peu près la moitié de la variance de forme dans notre échantillon peut s'expliquer par des différences spatiales, temporelles et environnementales, ainsi que par la grandeur, indiquant un degré de continuité démographique à travers une transmission culturelle soutenue. Une partie de la variance restante représente probablement des différences stylistiques entre assemblages, qui sont souvent un objet d'intérêt pour les études archéologiques. La nature très variable du MSA est-africain peut refléter un positionnement de la région en tant que refuge au sein du continent. La technologie des pointes représenterait un système adaptif flexible qui fut utilisé de manière dynamique à travers l'Afrique pendant le MSA en fonction de divers contextes sociaux et écologiques, entraînant l'apparition de formes d'outils 'génériques' et 'spécifiques' à des moments et des lieux particuliers.

Introduction

Lithic points are routinely used by archaeologists to order the prehistoric archaeological record both chronologically and spatially (Shott 2020). The presence of regionally variable points, along with other features, has been used to define the Middle Stone Age (MSA) since its inception (Goodwin and van Riet Lowe 1929). In eastern Africa, Clark (1988) asserted that the form of MSA points varies considerably, while also being distinctive from other regions of the continent. For example, he noted that in the Rift Valley unifacial and bifacial foliate and triangular points dominated MSA assemblages, while in the Horn of Africa there is much more technological and typological variability, such as leaf-shaped points from Porc-Epic, Ethiopia, and Levallois points from Midhishi, Somalia (Clark 1988). Although these early observations highlight how eastern African MSA points demonstrate marked patterns of formal variability, they have received relatively little attention beyond functional analyses when compared to other regions of the continent, such as northern and southern Africa. For example, in northern Africa, the Aterian industry is recognised by the presence of tanged points (Iovita 2011; Scerri and Spinapolice 2019), while in southern Africa affiliation to the Still Bay industry requires the presence of bifacial foliate points (Archer *et al.* 2016). Such distinctive point styles have been argued to represent the spatio-temporal distribution of specific regional cultures during the MSA (Clark 1988; McBrearty and Brooks 2000; Scerri and Will 2023).

Although archaeologists have similarly proposed variants for the eastern African MSA, these are usually limited to individual sites or simply borrow nomenclature from other regions (Shea 2020). As a result, eastern Africa does not have widely applied cultural phases that divide its MSA record. This makes it a particularly important laboratory for testing hypotheses about the causal mechanisms of variation observed in the 'generic' MSA record, i.e. assemblages that are deemed to be MSA but without any further cultural division. In a recent synthesis Scerri and Will (2023) proposed that the 'generic MSA' represents the base level technological manifestation of a major cognitive shift during the Middle Pleistocene, probably associated with the emergence of our species (Scerri *et al.* 2018), with the subsequent appearance (and disappearance) of 'specific' innovations reflective of the demographic, biogeographical and historically contingent trajectories of individual regional sub-populations. The MSA is polythetic, meaning that it is defined by a number of criteria, not all of which need to be met to be considered part of it. Points are held to be one of these defining features, yet their absence is not sufficient to exclude attributing an assemblage to the MSA. Additionally, certain types of points are seen to be indicative of specific cultural industries within the MSA; forms without distinct signs of regionalisation are, however, somewhat understudied (though see Douze *et al.* (2020), Timbrell *et al.* (2022a) and Schoville *et al.* (2023) for recent examples). Exploring why eastern Africa, and indeed other equatorial zones (Thompson *et al.* 2018; Niang *et al.* 2023), do not possess clear diagnostic tools remains an important task when attempting to understand the underlying cultural dynamics of MSA-making populations across Africa.

Due to the significance of point morphology to both the 'generic' and 'specific' MSA, and the potential link between point form and population dynamics during it, we present here a metric and geometric morphometric analysis of eastern African MSA points and evaluate the potential causal mechanisms of variation in them observed in the record.

Previous studies of eastern African Middle Stone Age points

'Point' has often been used interchangeably with 'projectile' as it has been considered likely that the artefacts in question were used as the hafted tips of thrown hunting armatures during the MSA (McBrearty and Brooks 2000). In eastern Africa, there is considerable evidence that points were indeed manufactured for projectile weaponry. For example, Sisk and Shea (2011) found that the bifacial and unifacial points at Porc-Epic had similar metrical properties to ethnographic dart tips, reinforcing a proposed projectile function. At Mumba Cave, Tanzania, evidence of hafting modifications, such as thinning and notching at the distal end, and macroscopic tip damage has also been suggested to demonstrate that MSA points were designed for insertion into wooden shafts to create arrows and spears (Bretzke *et al.* 2006; Bushozi 2011). Bretzke *et al.* (2006) compared the weight and tip cross-sectional area (TCSA) values of points from Mumba Cave with a published ethnographic dataset of thrown and thrusting spears, spear-thrower projectiles and arrows. Their results showed that, although not all examples could be confidently assigned to a specific projectile technology, the variation in these parameters indicate the co-existence of multiple weapons systems. Point shapes did not co-vary with size and therefore it was proposed that point morphology did not relate to function (Bretzke *et al.* 2006).

However, a homogenous conception of the MSA point as a projectile undermines evidence for other potential functions like cutting, incising and sawing from across the continent (e.g. Lombard 2007; Rots *et al.* 2011; Douze *et al.* 2020). Douze and Delagnes (2016), in their technological analysis of the early MSA points from the Gademotta and Kulkuletti site complex, Ethiopia, differentiated between point production involving shaping of undetermined blanks and that involving the retouching of predetermined blanks. They suggest that pointed forms achieved by shaping alone were likely multi-purpose tools, due to the presence of multiple functional edges, while those achieved via pre-determination and retouch were likely projectiles due to the penetrative potential of the tip. In analyses of the MSA assemblages at Aduma, also in Ethiopia, Sahle and Brooks (2019) found that point forms at the site change through time, with the oldest points showing larger dimensions and TCSA values than ethnographic spears. They suggested that this may represent a shift from simple spear technologies to more refined and complex projectiles.

Whether tool function can be inferred from technological or typological measures alone is debated, with some scholars stressing that microwear or residue evidence for hafting is essential for identifying 'points' and their function (Rots and Plisson 2014; Rots 2016). Rots and Plisson (2014) drew attention to the problematic nature of using such diagnostic features of impact damage, stating that, without detailed analyses of large reference collections of experimental tools, the reliability of the analogy is impossible to determine. Yet Sisk and Shea (2011) highlight that making references to ethnographic collections requires careful consideration as 'points' in museums are often biased towards those that are more heavily retouched. On the other hand, experimental work has demonstrated that unretouched, minimally retouched and wooden points may also have functioned adequately as projectiles (Sisk and Shea 2009; Waguespack *et al.* 2009), thus potentially leading to an under-appreciation of technological strategies for manufacturing hafted point technology in archaeological populations.

Points have been argued to represent the single artefact category within MSA toolkits that most likely reflects group identity and population structure (McBrearty and Brooks 2000; Wilkins 2010). This is because, ethnographically, arrows are traded between interacting groups when taken onto the hunting landscape and it is there that the need for emblematic social signalling arises (Sackett 1982; Tostevin 2012). Among the !Kung San of the Kalahari, for example, comparable designs are maintained among co-operating neighbours, often across large distances, to ensure that they can be used by several hunters within the '*hxaro*' exchange system (Wiessner 1977, 1982, 1983, 1985; Nicholas and Kramer 2001). Thus, although typology alone is unlikely to be useful for determining point function, point form is likely to be informative about shared cultural norms and group interaction.

Bushozi (2011) analysed 261 points from the MSA and MSA/LSA transitional layers at Nasera, Mumba and Magubike in Tanzania. His results demonstrate that at all three sites a consistent range of butt modification strategies and retouch modifications is present in both MSA and transitional assemblages, something that he interprets as representing continuity in regional traditions and the presence of complex population networks that shared technological knowledge. In a similar vein, two-dimensional geometric morphometric analyses of the full MSA sequence at Mumba have found consistently high morphological variability and no significant changes in shape through time, although it is suggested that this pattern demonstrates technological flexibility and the development of multiple hunting systems, rather than evidence for the maintenance of regional traditions (Bretzke and Conard 2017). As well as differences in methodology, it is possible that such differences in interpretation derive from taking a purely site-based approach over that which considers regional patterns of variability, with the addition of the spatial dimension by Bushozi (2011) indicating that certain aspects of technological variability were not only maintained from generation to generation but also across large areas. Temporal variation within a site can represent several processes, such as technological flexibility within a single population, adaptation to the environment within a single population and/or multiple populations with different technologies (Foley *et al.* 2013), the latter two echoing the famous Bordes-Binford debate regarding the interpretation of variability in Mousterian lithic assemblages of the Middle Palaeolithic (Bordes 1950; Binford and Binford 1966). Patterns of chronological variability can therefore reflect a variety of evolutionary factors, as opposed to being purely functional or stylistic. It is thus imperative to establish the theoretical expectations of variation deriving from culturally transmitted style as opposed to that which is adaptative and thus probably linked to tool functionality, as well as to recognise the impact of additional factors like raw material and life history on point morphology.

Theoretical expectations of point variability in archaeological populations

Interpretations of archaeological similarities and differences in relation to population structure need to consider that other forms of cultural evolution can generate patterns of variability. Isolation-by-distance (IBD), isolation-by-time (IBT) and isolation-by-environment (IBE), originally developed from genetic theory (Wright 1943), can thus be utilised as null models. Within the context of archaeological data, cultural transmission and the transfer of skills depends on close interaction between individuals through space (Tostevin 2012). Interaction declines with geographic distance such that, when controlling for other confounding factors, similarity in transmitted cultural diversity has also been found to decrease (Neiman 1995; Shennan 2020). Under IBD in archaeology, similarities are expected between proximal sites, as the generation of novel variation (innovation) in one place is less likely to be transmitted to populations further way than those at proximity. Temporal change results from the random loss or gain of variants during transmission through time (drift), with archaeological similarities expected between sites of similar ages under IBT (Shennan 2020). Similarities in assemblages may also represent comparable adaptive solutions to similar environmental contexts (IBE). Large-scale patterns of IBE could be a form of environmentally driven convergence in some (but not all) cases, with cultural similarities appearing between assemblages that are widely separated in terms of space and/or time but share similar environmental conditions. In such cases, the appearance of similar but independently derived technological solutions may be a more parsimonious explanation than cultural transmission over such vast spatiotemporal distances.

Patterns of IBD and IBE are likely to be highly correlated because populations that share the same geography probably also share similar environments, thereby generating similar patterns. Moreover, archaeological diversity is both spatially and temporally autocorrelated. In other words, differences between any two entities increase as a function of the temporal and spatial distance between them (Loog *et al.* 2017). The extent to which spatial differences contribute to cultural diversity relies heavily on population structure and mobility, with low mobility leading to strong spatial structure. This means that in low-mobility populations differences between populations are more likely to be more strongly correlated with space than with time (Loog *et al.* 2017). Applying this logic, Blinkhorn and Grove (2021) used a highly correlated 'timespace' variable that recognised the combined influence of space and time and found that it exhibits a stronger and independent correlation to eastern African MSA variability than other spatial variables, emphasising the potential role of cultural transmission and inheritance on assemblage similarity during the MSA.

Because points are tools, certain aspects of their morphology are likely to be influenced by the selective environment in which design choices affect performance. During the MSA (and indeed other prehistoric phases), point designs were likely modified over time due to small copying errors or innovations arising through trial and error. Modifications that increased performance during the intended task would have likely been 'selected for' and passed on to the next generation (Dunnell 1978). Stylistic variability concerns the aspects of shape that have social rather than subsistence functions (Sackett 1982) and are therefore not directly conditioned by the selective environment. These aspects of point typology are thought to be more prone to random drift through the accumulation of copying errors over time. White (2013) hypothesised that the width and thickness of the hafted end most likely relate to functional variability due to the requirement for the point to be inserted into a shaft, with stylistic attributes appearing more variable because random drift causes differentiation through time and space without constraint by the selective environment. Conversely, recent work by Schoville *et al.* (2023) found that the proximal end has greater shape variation than the distal end of unretouched MSA points. Style can, however, be both active and passive: MSA populations may have actively incorporated style into their point designs to demonstrate group affiliation and facilitate the formation of social networks, as seen in !Kung *hxaro* networks (Wiessner 1983) or certain styles may have unconsciously emerged because of related technological and cultural traditions (Dunnell 1978; Sackett 1982). Under both scenarios, stylistic choices may have been shaped by social conformity, which exerted a selective force on point typology that is unrelated to subsistence function. Historically, a strict dichotomy between style and function has been argued by evolutionary archaeologists (Dunnell 1978; Neiman 1995). However, Shennan and Wilkinson (2001) contended that there is not a radical distinction between style and function and that both drift and selection likely operate within a broad spectrum of possibilities. Moreover, unlike genetic change, cultural change involves horizontal transmission and can occur very quickly; differences in point morphology are therefore not simply the result of natural selection and drift *sensu stricto* (Collard *et al.* 2008). Nonetheless, ascertaining which aspects of point shape are more likely to be linked to functional versus stylistic variability is an important task when using tool morphology as a proxy for cultural contact and exchange.

Scerri (2013) has suggested that population structure is best inferred archaeologically through analyses conducted at the assemblage level. This is because the complexity of group boundaries may manifest themselves in similarities between some assemblage components with differences in others. Under this model, group boundaries are most clearly structured when there are strong differences in hafted stylistic tools between assemblages while blank manufacture and hand-held and heavy toolkit morphology remain similar. However, when similarities in hafted tools exist between assemblages, group structure is either weak/permeable or spatially autocorrelated. This confirms that, although assemblage-level studies potentially give a more holistic account, hafted tools (like points) are particularly informative about cultural transmission and group identity during the MSA and are the key driver of patterns relating to population structure in archaeological assemblages. Blinkhorn and Grove (2018, 2021) and Timbrell *et al.* (2022b) have conducted assemblage-level analyses of structure in the eastern African MSA using multiple matrix regressions. Here, we use outline-based geometric morphometrics and metric methods in conjunction with these multivariate methods to explore potential drivers of shape variability in eastern African MSA points. Both approaches offer complementary but varied insights into prehistoric population dynamics, with the presence and absence of different artefacts useful for demonstrating the varying constellations of behaviours apparent throughout the MSA and typological data from MSA points potentially informative about the nature of group interaction through time and space.

We have developed a series of null hypotheses that distinguish between point diversity related to various types of autocorrelations (H_0). In the context of cultural variability, autocorrelation refers to the phenomenon that adjacent observations tend to show similarities as a consequence of the spatiotemporal and biogeographic distribution of the samples studied. It must be noted that these autocorrelation null models represent idealised theoretical states; the imperfect nature of the archaeological record means that it is largely impossible to have samples that are completely isolated along only one dimension. Nonetheless, models based on regression statistics can identify independent relationships between cultural variability and space, time, and environments through controlling for the effects of other confounding variables and can therefore effectively test these three hypotheses:

H_{0a} *Isolation by distance*

Differences between points will not tend to be observed in assemblages that are geographically proximal, controlling for the effects of time and environments;

H_{0b} *Isolation by time*

Differences in points will not tend to be observed in assemblages that are chronologically proximal, controlling for the effects of space and environments; and

H_{0c} *Isolation by environments*

Differences in points will not tend to be observed between assemblages occupying similar environments, controlling for the effects of time and space.

Materials

To study the structure of eastern African MSA point variability, artefact samples were accessed via a collaborative data collection framework (Timbrell 2022; Timbrell *et al.* 2022c) with the National Museums of Kenya and the National Museum of Ethiopia. Table 1, Figure 1 and Supplementary Figure S1 describes the sample, which includes artefacts from both dated and undated layers, with date ranges rounded to the nearest 1000 years. In total, 218 eastern African MSA points were studied from six sites: Porc-Epic, Goda Buticha, Kapthurin Formation, Prospect Farm, Prolonged Drift and Omo

Table 1. A summary of the eastern African Middle Stone Age point sample studied in this paper. Samples without information regarding assemblage attribution and/or surface finds are left unassigned and were removed from analyses beyond the site-level. Assemblage locations are abbreviated thus: NME National Museum of Ethiopia (Addis Ababa); NMK National Museums of Kenya (Nairobi).

Site	Location	Latitude	Longitude	Assemblage	Minimum age (kya)	Midpoint age (kya)	Maximum age (kya)	N	Length		Width		Thickness		Reference
									Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	
Kapthurin Formation (N = 13)	NMK	0.52	35.9	GnJh-15	396	431	465	5	25.6	11.2	18.2	10.2	6.4	3.3	Deino and McBrearty (2002)
				GnJh-78		100		9	54.1	15.8	35.5	8.4	10.2	2.4	Blegen *et al.* (2018)
Prolonged Drift (N = 8)	NMK	-0.48	36.1	GrJi 11	30	51	72	8	44.6	8.6	26.1	5.0	8.6	2.2	Merrick (1975)
Prospect Farm (N = 78)	NMK	-0.59	36.18	GsJi 8	50	85	120	56	46.5	10.8	30.2	7.8	10.2	3.2	Anthony (1978)
				GsJi 7	50	85	120	22	36.7	7.9	24.2	6.2	8.7	3.0	Anthony (1978)
Goda Buticha (N = 32)	NME	9.54	41.63	Complex II IIa–c	4	6	8	8	40.4	16.5	19.3	3.9	7.4	1.6	Tribolo *et al.* (2017)
				Complex II IId–f	33	41	48	13	36.2	6.8	19.1	4.8	6.5	1.8	Tribolo *et al.* (2017)
				N/A				13							Tribolo *et al.* (2017)
Omo Kibish (N = 12)	NME	5.41	35.9	BNS	93	111	123	4	46.4	19.0	30.7	10.3	9.3	3.2	Shea (2008)
				AHS	195	200	205	6	53.7	14.1	34.0	4.5	9.9	3.1	Shea (2008)
				N/A				2							Shea (2008)
Porc-Epic (N = 74)	NME	9.63	41.87	08N-07W IIIa		40		22	44.7	10.1	23.7	4.6	8.6	2.4	Pleurdeau (2005)
				08N-07W IIIb		40		23	44.5	10.6	22.5	4.6	7.5	2.1	Pleurdeau (2005)
				08N-07W IIIc		40		10	45.6	10.3	26.1	10.6	7.6	2.7	Pleurdeau (2005)
				08N-07W IIId		40		4	45.4	11.5	31.2	7.6	8.6	1.5	Pleurdeau (2005)
				06N-14W 60–200cm		40		14	40.9	4.6	21.8	3.0	8.1	1.6	Pleurdeau (2005)
				N/A				2							Pleurdeau (2005)

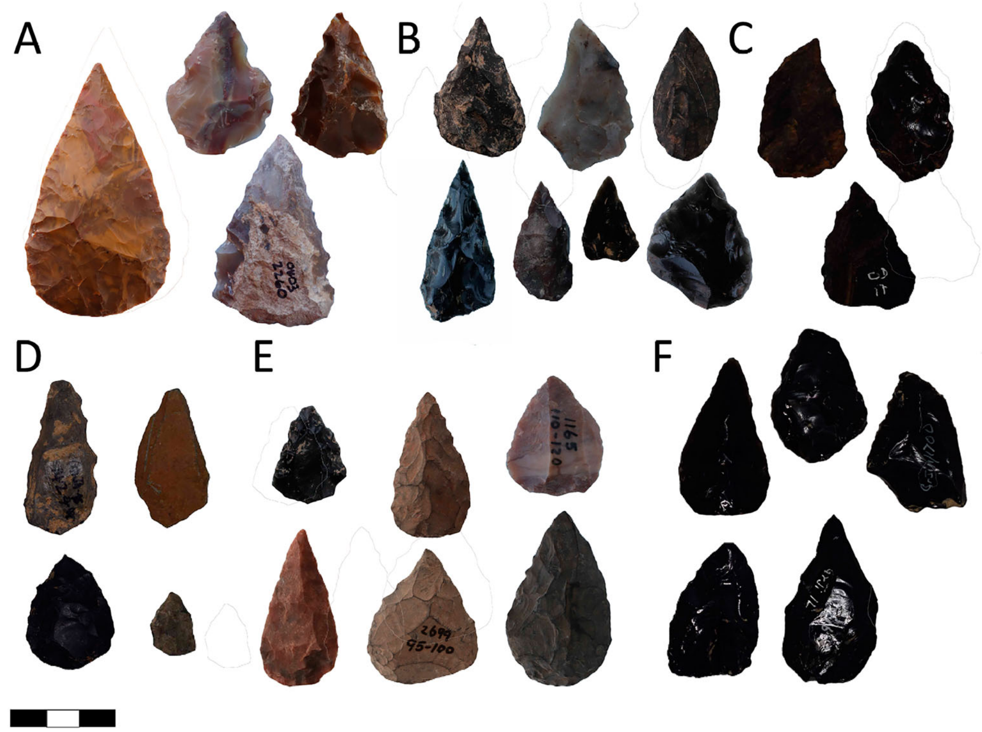

Figure 1. Sample of Middle Stone Age points analysed from Omo Kibish (A), Goda Buticha (B), Prospect Farm (C), Kapthurin Formation (D), Porc-Epic (E) and Prolonged Drift (F).

Kibish. Further background to each site is provided in Supplementary Online Material S1. Some points were surface finds and/or did not have information regarding the assemblage to which they belong and were omitted from analyses conducted beyond the site-level. Thirteen assemblages were studied, many with only a small sample of points. Caution must therefore be observed when interpreting the statistical results. MSA points are often at relatively low densities compared to other tool types. The results obtained from these small samples can nevertheless be used to indicate trends that should be tested with further data.

Points were selected following the definition outlined by Shea (2020): "bilaterally symmetrical, broadly triangular flakes with retouched lateral edges that converge at their distal edge." This definition is primarily a typological one, with the addition of retouching as a technological requirement. Points do not necessarily have to be retouched (i.e. Douze *et al.* 2020; Timbrell *et al.* 2022a), but because their shape is used here as a proxy for shared cultural traditions the emphasis on retouching as a control on shape is particularly important. Moreover, Scerri (2013) proposed that variability in hafted tools is most likely to be indicative of group dynamics. While points do not have to be retouched to be hafted (Sisk and Shea 2009; Waguespack *et al.* 2009), hafting encourages standardised tool designs to ensure a good fit and therefore points that are retouched are somewhat more likely to have been hafted tools. Other hafted tools, like backed pieces, may also be informative (e.g. Way *et al.* 2022), although we have focused on points here due to their significance for both the 'generic' and 'specific' MSA.

We applied outline-based geometric morphometrics (GMM) methods due to their suitability for studying lithic material (Matzig *et al.* 2021). To ensure that all aspects of the outline were culturally significant, any points with tip damage or blunting were removed. Raw materials were determined macroscopically. The sample was predominately made from obsidian (N = 106), chert (N = 61) and basalt (N = 46), with much smaller frequencies of rhyolite (N = 3), quartzite (N = 1) and fossilised wood (N = 1). We studied the effects of raw materials on point shape and form and found some significant differences, particularly between obsidian and chert. These results are reported in Supplementary Online Material S2.

Methods

All of the data and code for the analyses can be found on the GitHub repository for the project at https://github.com/lucytimbrell/EA_MSApoints

Metric analysis

Following the protocols outlined in Timbrell (2022), three basic measurements were taken to record morphological length, width and thickness at a resolution of 0.1 mm. We defined length as the maximum dimension of the point, width as the maximum measurement in the perpendicular dimension to length and thickness as the maximum measurement in the third dimension, following Shea (2020). One point (E_point_142) from Kapthurin Formation did not have its metric measurements recorded and was thus removed from the metric analysis.

Geometric morphometric analysis

We also performed two-dimensional geometric morphometrics on the photographs of the points taken via collaborative data collection as outlined and validated in Timbrell (2022) and Timbrell *et al.* (2022c). The protocols optimised the photographs for outline-based GMM, including the use of a scale and minimising of shadows around the object. Each point was oriented and levelled across two planes (tip-base axis and side-to-side axis) to minimise additional sources of error during photography (Timbrell 2022).

In preparation for the GMM analysis, each image was processed using the 'object select' tool in Adobe Photoshop, which automatically determines the object's contour. Once this was highlighted, the object was filled with solid black to help facilitate the extraction of outline data. All processed images were then synthesised into a single thin-plate spline (.tps) file using tpsUtil (Rohlf 2004a) and the outline data extracted using tpsDig2 (Rohlf 2004b). The outline of each artefact was represented by an average of 1755 equidistant points, which were scaled through the specification of the pixel-to-centimetre ratio for each image. The outline data were saved as (x, y) co-ordinates within the .tps file and imported into R.

Using the "Momocs" R package (Bonhomme *et al.* 2014), the outlines were then standardised following Bonhomme *et al.* (2017) by normalising them to a common centroid, scaling to centroid size and aligning along the long axis of the object. We then performed elliptic Fourier analysis (EFA) to convert the geometric data to frequency data, with the outline decomposed into a series of repeating trigonometric functions, referred to as harmonics (Caple *et al.* 2017). The appropriate number of harmonics was identified to capture sufficient information on shape using the 'calibrate_harmonicpower_efourier' function in Momocs. We retained ten harmonics for 99% harmonic power.

To explore the potential drivers of shape variability within the sample, we applied a range of statistical techniques. First, we performed a Principal Components Analysis (PCA) to reduce the dimensionality of the shape data (i.e. the harmonics). To assess the relationship between centroid size and the most heavily weighted principal components (PCs), as well as length, width and thickness metrics, we also performed correlation and linear regression analyses. We performed multivariate analysis of variance (MANOVA), analysis of variance (ANOVA) and Tukey's Honestly Significant Difference (HSD) tests on the PC scores representative of 90% of the total variance to further assess the statistical significance of differences between raw materials, sites and assemblages. We performed a hierarchical cluster analysis on these PCs, specifically the complete method to ascertain the structure of variation between sites. Lastly, we calculated the mean shape of each assemblage using the 'mshapes' function in Momocs (Bonhomme *et al.* 2014) and extracted the mean PC scores to act as the cultural data for each assemblage in the subsequent matrix regressions.

Matrix regressions

To evaluate point shape variability in terms of isolation by distance, time and environment, we first produced a cost path using Toblers Hiking Function (Tobler 1993) between the site co-ordinates as a measure of distance using a global relief model (GEBCO 2020). The maximum speed of off-path hiking (in km/h) is calculated as:

[1] $s = 6e^{-3.5|m + 0.05|}$

Tobler's Hiking function is not symmetric around 0 because humans tend to walk fastest on gently downward slopes ($m = -0.05$) compared to flat terrain ($m = 0$). To compute a transition layer using the Hiking Function, we calculated the slope m of the terrain from the altitude z and the distance between cell centres d of each DEM for each pair of cells i and j:

[2] $m_{ij} = (z_j - z_i)/d_{ij}$

This was performed using the gdistance package in R (van Etten 2017), with major water bodies masked from the analysis.

The slope (m) was then used to calculate the travel time T in hours of moving between cells of the DEM using the reciprocal of Tobler Hiking Function:

[3] $T = (1/6)e^{3.5|m + 0.05|}$

Finally, a correction procedure was employed to consider the distance between cell centres, as when travelling with the same speed a diagonal connection between cells takes longer to cross than a straight connection.

For chronology, we used the mid-point in the dating error range as a simple estimation of age for each assemblage following Blinkhorn and Grove (2018, 2021) and Timbrell *et al.* (2022b), but noting that for some assemblages this spans several tens of thousands of years (Table 1). It must also be noted that some of the assemblages studied rely on dating methods nowadays deemed unreliable (e.g. obsidian rehydration; see Supplementary Online Materials S1), making the chronological control of the analysis poor in places. Because the analysis is performed at a regional sale, a compromise on chronological resolution is nonetheless necessary to expand the temporal window to get a sufficient sample of assemblages for robust analyses.

Lastly, to produce a characterisation of the environment of each assemblage, we extracted the temperature (bio01) and precipitation (bio12) values from the climate model of Krapp *et al.* (2021) at the site co-ordinates in the time-slice representative of the simple age, following the methodology outlined in Timbrell *et al.* (2022b) and Leonardi *et al.* (2023). Although proxy data (when available) provide the most accurate information about the environmental conditions at archaeological sites, such data are often highly variable and, in most cases, not recovered in direct association with archaeological finds; model data provide a statistically valid means to capture the climatic conditions specific to the time period of each site and were thus employed here (see Timbrell *et al.* 2022b for further discussion).

Together, these provided measures of distance, time and environment that were then assessed against mean point shape for each assemblage using multiple matrix regressions, controlling for size (characterised by the metric measurements) and raw material. Raw materials were converted to binary data, following Blinkhorn and Grove (2018), to demonstrate the presence and absence of each within each point assemblage. Multiple matrix regression was performed with 999 permutations used to determine p-values applying functions from the 'phytools' package in R (Revell 2012).

Results

Shape variability in eastern African MSA points

PCA yielded six principal components (PCs) that represent >90% of the total variance in the data. Figure 2 highlights the shape differences along each principal component. PC1 represents 63.4% of the total variance and is an axis of elongation, with negatively scoring points demonstrating long, thin shapes and positively scoring points having wide, short morphologies. PC2 and PC3 represent 11.2% and 8.7% of the total variance respectively and mark an asymmetrical shape difference between more triangular morphologies with acute tips and more rectangular morphologies with obtuse tips, with mirrored convexities along each lateral edge. PC4 represents 4.6% of the total variance and represents asymmetrical shape differences between points with acute tips with convexity on the left or right lateral edge. PC5 represents an axis of tip narrowing from negative to positive, with a slight convexity of the base in the positive direction, which makes up 2.6% of the total variance. PC6 also represents 2.6% of the total variance and reflects a similar axis of variance to PC5, although the convexity of the base is expressed more asymmetrically and it also occurs on negatively scoring points with obtuse tip angles.

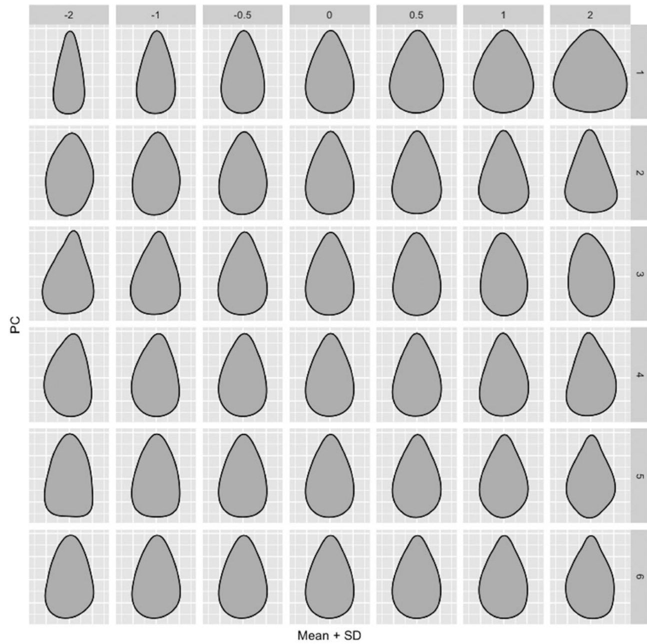

Figure 2. Principal component (PC) contributions, highlighting the mean and standard deviation (SD) shape changes along PC 1–6.

Relationship between shape and size

To understand how size and shape are related, we regressed centroid size against each principal component (Supplementary Figure S2, Table S1). PC1 demonstrates a statistically significant relationship with centroid size, with points demonstrating wider morphologies tending to be larger than those with thinner shapes. The R^2 value (0.13) highlights that allometry accounts for around 13% of the variance in elongation. PC2 through PC5 also show statistically significant relationships with centroid size, although these relationships are much weaker. There are also some clear outliers in terms of size from these plots, but their shape clearly meets the definition of a point (Supplementary Figure S3). They were therefore retained in the analysis. Overall, the results highlight that allometry is present within the data and that point form (shape + size) should be explored as well as shape.

Inter-site shape variability

Next, we tested whether there are shape and size differences between points from different sites. Figure 3 and Supplementary Table S2 describe the distribution of length, width and thickness according to the sites. Kaputhurin Formation is the most variable site, Prolonged Drift is the least variable (Figure 3, Supplementary Table S2). Tukey HSD analysis confirmed that points from Goda Buticha are significantly shorter than those from Omo Kibish and narrower than those from Omo Kibish, Kapthurin Formation and Porc-Epic (Table 2). Points from Kapthurin Formation and Goda Buticha also show significant differences in width, as do those from Prospect Farm and Porc-

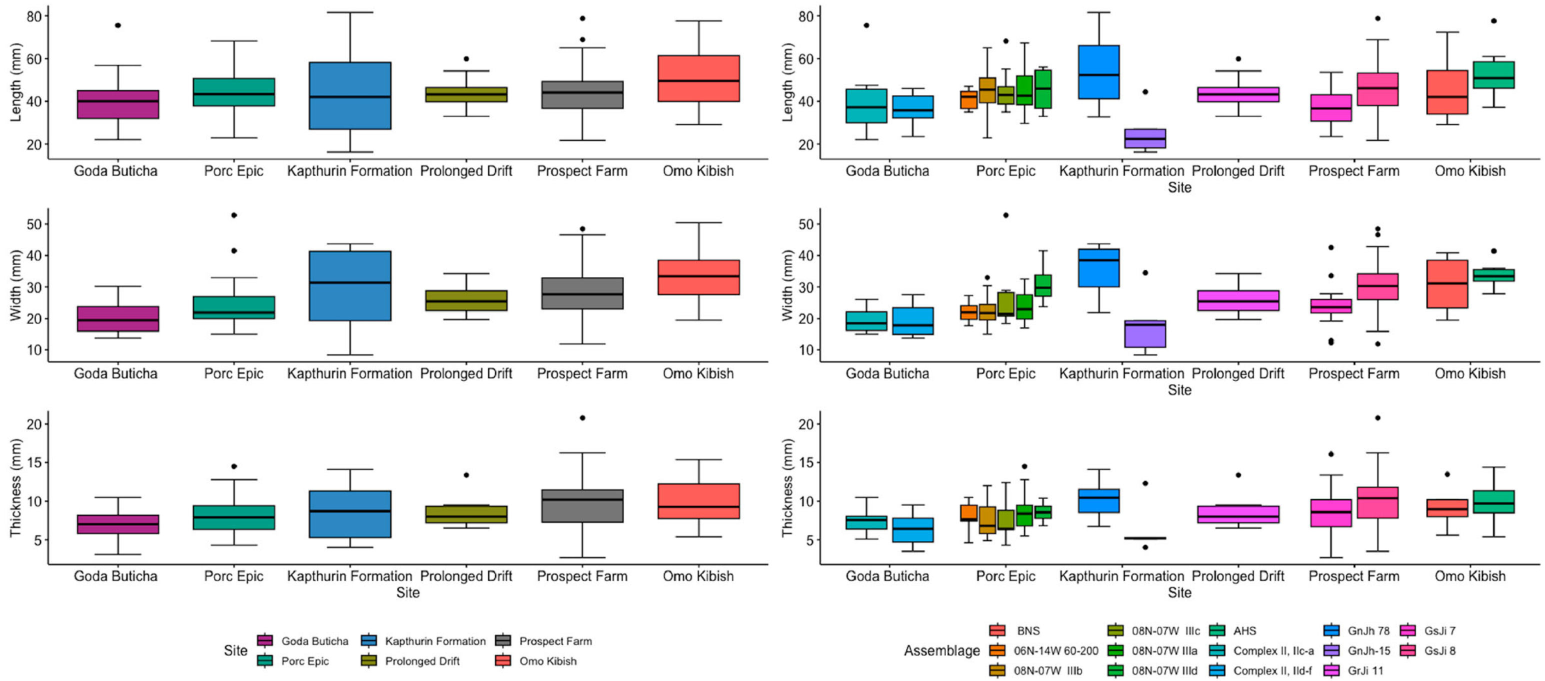

Figure 3. Boxplots of point length, width and thickness (mm) for each site (left) and assemblage (right).

Table 2. Eastern African Middle Stone Age points analysed in this study: p-values from Tukey Honestly Significant Difference analyses for length, width and thickness as well as principal components (PC) 1, 3 and 6. Statistical significance is highlighted at p < 0.05 (*) and at p < 0.01 (**). All values have been rounded to three decimal places.

	Length	Width	Thickness	PC1	PC3	PC6
Kapthurin Formation - Goda Buticha	0.945	0.004**	0.314	0.058	0.007**	0.999
Omo Kibish – Goda Buticha	0.049*	<0.001**	0.021*	0.004**	0.925	0.129
Porc-Epic – Goda Buticha	0.408	0.230	0.400	0.925	0.215	0.991
Prolonged Drift – Goda Buticha	0.895	0.310	0.618	0.753	0.999	0.013*
Prospect Farm – Goda Buticha	0.567	<0.001**	<0.001**	<0.001**	0.052*	0.664
Omo Kibish – Kapthurin Formation	0.535	0.554	0.919	0.955	0.004**	0.403
Porc-Epic – Kapthurin Formation	0.999	0.150	0.944	0.166	<0.001**	0.999
Prolonged Drift – Kapthurin Formation	1.000	0.956	1.000	0.962	0.115	0.0711
Prospect Farm - Kaputhurin Formation	1.000	1.000	0.806	0.946	0.471	0.976
Porc-Epic – Omo Kibish	0.435	<0.001**	0.262	0.013*	0.997	0.192
Prolonged Drift – Omo Kibish	0.827	0.195	0.919	0.635	0.981	0.910
Prospect Farm – Omo Kibish	0.326	0.196	1.000	0.999	0.035	0.524
Prolonged Drift – Porc-Epic	1.000	0.939	0.992	0.949	0.805	0.020*
Prospect Farm – Porc-Epic	0.999	<0.001**	0.001**	<0.001**	<0.001**	0.852
Prospect Farm – Prolonged Drift	1.000	0.943	0.852	0.539	0.574	0.081

Epic (Table 2). In terms of thickness, the Goda Buticha points show significantly lower values than points from Omo Kibish and Prospect Farm, with Porc-Epic's points also being significantly thinner than those from Prospect Farm (Supplementary Table S2, Table 2).

GMM analysis confirmed the presence of statistically significant differences in point shape between the sites (MANOVA: Hotelling-Lawley = 1.0062, approximate F = 5.116, $p < 0.001$). Figure 4 highlights how Goda Buticha and Porc-Epic score more negatively along PC1 compared to the other sites, as they tend to show more elongated morphologies. Along PC3, Prospect Farm and Kapthurin Formation tend to score more positively, suggesting that points from these sites tend to demonstrate more obtuse tip angles (Figure 4). Along PC6, Prolonged Drift tends to score more negatively compared to the other sites (Figure 4), Tukey HSD results on ANOVA scores for each principal component are listed in Table 2, highlighting the existence of many key differences between sites across multiple dimensions.

A hierarchical cluster analysis found that there is some structuring by site, with points from certain sites clustering closely together (Supplementary Figure S4). Splitting the tree into six clusters (the number of sites) demonstrates that points from Kapthurin Formation and Prolonged Drift form tight groups within Cluster 5 and that those from Omo Kibish form a tight group within Cluster 3. However, points from Prospect Farm appear in five clusters, Goda Buticha points appear in four and Porc-Epic in three, suggesting that the main structure of variability within the sample does not necessarily correspond with site attribution, confirming Clark's (1988) observation of high inter and intra-site variability in eastern Africa and implicating other potential factors, such as those related to the environment.

Inter-assemblage variability

We then analysed point variance between assemblages. Table 1 reports summary statistics for each assemblage and Figure 3 demonstrates boxplots of length, width and

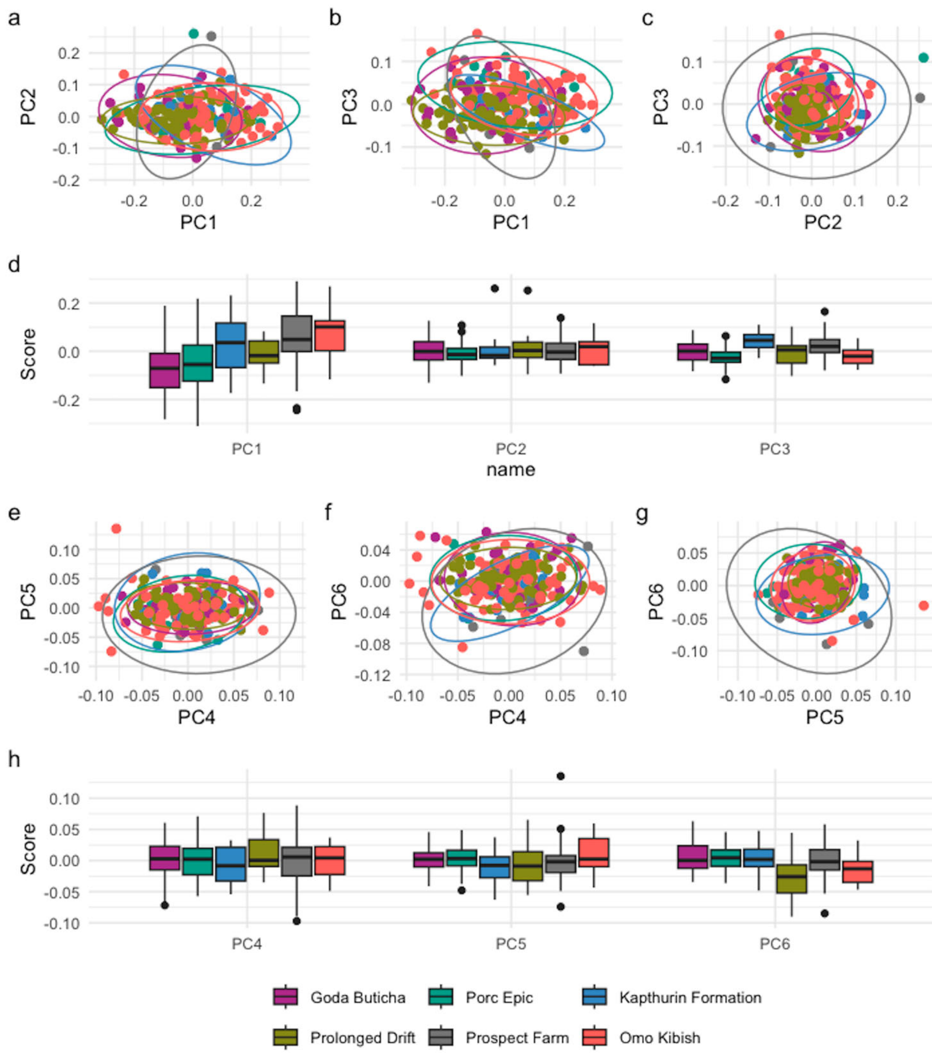

Figure 4. Principal components analysis (PCA) scatterplots and boxplots of principal component (PC) 1–3 (a–d) and PC 4–6 (e–h) for each site.

thickness. Interestingly, some sites (i.e. Goda Buticha) demonstrate relatively low variance between assemblages (Table 1), whereas others (Kaputhurin Formation, Prospect Farm) show much higher diversity between assemblages, something confirmed to be statistically significant by post-hoc Tukey HSD tests (Kapthurin assemblages: $p < 0.001$, Prospect Farm assemblages: $p = 0.02$; Supplementary Table S3). Points from GnJh-78 and GsJi 8 are relatively longer, wider and thicker than those from GnJh-15 and GsJi 7 respectively (Table 1). Supplementary Table S3 also highlights how differences tend to be seen between assemblages from the Ethiopian Rift and the Kenyan Rift, as well as those within the Kenyan Rift, indicating a degree of spatial structure to the variability.

GMM analyses highlighted significant variability in shape between the assemblages (MANOVA: Hotelling-Lawley = 1.540, approximate F = 2.67, $p < 0.001$), with PC1, PC3 and PC6 yielding significant differences (Figure 4, Supplementary Table S3). Along PC1, 08N-07W IIIb (Porc-Epic) and the two assemblages from Prospect Farm (GsJi 7 and GsJi 8) show significant differences, with the assemblage from Porc-Epic having elongated points compared to those from Prospect Farm (Figure 4). GsJi 8 also shows significant differences to Complex II, IIc-a from Goda Buticha (Supplementary Table S3). Along PC3, all five of the assemblages from Porc-Epic show significant differences to GsJi 7 from Prospect Farm, with 08N-07W IIIa-c also displaying differences to GsJi 8 at Prospect Farm (Supplementary Table S3). All the Porc-Epic assemblages additionally show distinctions to GhJh 78 from Kapthurin Formation along PC3 with 08N-07W IIIa and 08N-07W IIIc also exhibiting differences to GnJh 15, Kapthurin Formation (Supplementary Table S3). Along PC6, the assemblage from Prolonged Drift, GrJi 11, and GsJi 7 from Prospect Farm both show disparities to 08N-07W IIIa from Porc-Epic and Complex II, IId-f from Goda Buticha (Supplementary Table S3).

We then calculated the mean point shape for each assemblage (Supplementary Table S4 and Figure S5). Point shape appears relatively regular at Porc-Epic, with highly symmetrical elongated morphologies with acute tips seen in four out of five assemblages. 08N-07W IIId is differentiated to the other Porc-Epic assemblages, appearing much wider, more asymmetrical and triangular shaped, as well as more standardised along PC1 (sd = 0.035), yet more variable along PC2 (sd = 0.035) than the other assemblages from the site (Supplementary Table S4). Similar mean shapes to that just described are also reported for AHS (Omo Kibish) and GsJi 7 (Prospect Farm), with BNS sharing some similarities but also having further convexity in the base. Mean shapes for both the Goda Buticha assemblages are elongated and thin, bearing similarities to the other assemblages at nearby Porc-Epic (Supplementary Table S4 and Figure S5) Both of the assemblages from Kapthurin Formation demonstrate mean point shapes with relatively obtuse tip angles, with GnJh 15 in particular being asymmetrical; GnJh 15 is the least standardised assemblage along PC1 and PC2 (PC1 sd = 0.153, PC2 sd = 0.118; Supplementary Table S4). GsJi 11 from Prolonged Drift exhibits a relatively unique mean shape in that it exhibits extended right lateral convexity, though the rest of its morphology bears similarities to the assemblages from Kapthurin Formation (Supplementary Table S4 and Figure S5).

Evaluation of point shape in relation to null models

To tease apart potential independent drivers of variation between point assemblages, such as those deriving from isolation by distance, time and environments, we performed a series of multiple matrix regressions using the mean point shapes (Supplementary Table S4 and Figure S5). Table 3 reports the results for each principal component as well as an overall model for all of them. PC1 was found to have significant independent relationships with time ($p = 0.001$), space ($p = 0.002$) and environment ($p = 0.006$), with time and space having similar positive effects (time coefficient = 0.43, space coefficient = 0.47), precipitation a negative one (-0.38; Table 3). A negative relationship suggests that as variation in one variable increases (PC1), the other decreases (precipitation). Because PC1 represents 63% of the total variance, the model for this principal component explains 28% of the variance in the data, calculated as the proportion of variance explained by the model (R^2) multiplied by the proportion of the variance explained by the component (Table 3). PC3 has an independent significant relationship with space

Table 3. Multiple matrix regression standardised test statistics and adjusted R^2 for principal components (PC) 1–6, as well as an overall model incorporating all six principal components, for the eastern African Middle Stone Age point sample analysed in this study. The variance and the percentage of shape data explained by each principal component are given, as well as the percentage of shape data explained by the overall model (%), calculated by multiplying the percentage variance of each principal component with the model's R^2 value. Those relationships that are significant at $p < 0.05$ are shaded grey.

	Length	Width	Thickness	Raw mat	Time	Space	Precipit-ation	Temper-ature	R^2	%
PC1 (63%)	-0.674	0.720	-0.353	-0.066	0.436	0.477	-0.379	-0.101	0.445	28.0
PC2 (11.2%)	0.283	-0.152	0.027	0.195	0.418	-0.171	0.344	-0.171	0.692	7.8
PC3 (8.7%)	0.786	-0.350	-0.083	-0.158	-0.133	0.245	0.187	-0.137	0.435	3.8
PC4 (4.6%)	-0.050	-0.019	0.044	-0.076	0.294	-0.155	0.109	0.018	0.102	0.4
PC5 (2.6%)	-0.297	0.060	-0.044	-0.229	0.617	-0.028	0.065	0.262	0.387	1.0
PC6 (2.6%)	-0.290	-0.122	0.442	0.208	0.113	-0.016	0.172	0.175	0.243	0.6
Overall shape (90%)	-0.419	0.591	-0.295	-0.052	0.495	0.411	-0.243	-0.103	0.497	44.7

(p = 0.036), while PC5 has an independent significant relationship with time (Table 3). Length and width have significant independent effects on PC1 (an axis characterised by elongation) and PC3 (an axis characterised by tip narrowing; Table 3). Raw material does not have a significant independent effect on any of the principal components (Table 3). The final model found that distance through time, space and environment have significant independent effects on point shape variability, with all the variables together explaining 44.7% of the variance in the shape data (Table 3). This highlights the importance of isolation by distance, time and environments in generating patterns of diversity between eastern African MSA assemblages.

Next, we ran multiple matrix regressions on the metric dimensions to ascertain the independent effects of geographic distance, time, environment and raw material on point form. Width ($p = 0.001$) and time ($p = 0.027$) have a significant independent effect on length (Table 4). Length ($p = 0.001$), thickness ($p = 0.002$) and raw material types ($p = 0.045$) all have independent significant relationships with width (Table 4). Thickness has a significant relationship with width ($p = 0.02$) and space ($p = 0.02$; Table 4). Correlations between the measures of size affirm the common shape of MSA points because as one metric increases the others also increase. The final model, incorporating all three dimensions to characterise overall point form, found only time to have a significant independent effect, with the overall model also being significant ($p = 0.001$; Table 4).

Table 4. Eastern African Middle Stone Age points analysed in this study: multiple matrix regression standardised test statistics and adjusted R^2 for length, width and thickness in addition to the other variables, as well as an overall model incorporating all three dimensions (form). Those relationships that are significant at $p < 0.05$ are shaded grey.

	Length	Width	Thickness	Raw material	Time	Space	Precipitation	Temperature	R^2
Length	NA	0.421	0.103	0.160	0.371	-0.139	0.127	-0.145	0.695
Width	0.608	NA	0.468	-0.206	-0.208	0.034	-0.049	0.201	0.640
Thickness	0.183	0.576	NA	0.002	0.076	0.189	-0.150	-0.07	0.568
Overall form	NA	NA	NA	-0.050	0.445	-0.002	0.002	-0.013	0.320

Discussion

We have presented here a quantified evaluation of stone point variability that supports Clark's (1988) assertion of considerable differences in point shape and form both between and within eastern African MSA sites. Isolation by distance, time and environment are found to be key, independent drivers of point shape variability. However, not all the diversity seen in eastern African MSA points can be explained by these null models. In fact, over half of the variability in point shape is unexplained by the model, which could imply that the majority of point typology reflects other aspects of cultural variation. Overall, point styles are likely to be structured through space and time as a result of cultural transmission between interacting individuals, although the patterning observed here indicates that random variation also contributes to point diversity between eastern African MSA assemblages.

Raw material use did not have a significant independent effect on point shape diversity between assemblages, as has been suggested elsewhere in the literature (Andrefsky 1994; Manninen and Knuttson 2014; cf. Timbrell *et al.* 2022a). Instead, significant differences between the shapes of obsidian and chert points aligns with the unequal spatial distribution of raw materials across the landscape, with the differences between raw materials subsumed by those in distance. Spatial variability is found to be an independent driver of point shape variability between assemblages, particularly along the latitudinal axis. Shea (2008) compared the whole MSA assemblage from Omo Kibish and Porc-Epic, in addition to those from Gademotta/Kulkuletti and the Middle Awash, and found notable technological similarities, including the formal characteristics of points, proposing that early *H. sapiens* were practising similar technological behaviour throughout southern and central Ethiopia between 80 and 200 kya. Our own geometric morphometrics analysis confirmed that there are no significant differences between point shapes from this area of eastern Africa. For example, points from Goda Buticha, southeastern Ethiopia, were found to exhibit similar morphologies despite a large chronological gap between occupations, potentially indicating the maintenance of MSA cultural traditions into the Holocene (Pleurdeau *et al.* 2014) or the site's reoccupation following regional migrations from refugia (Tribolo *et al.* 2017). Point morphologies from within the Central Kenyan Rift were also not found to be significantly different from each other in any shape dimension (i.e. the principal components). Broadly, latitudinal differences in point shapes can be characterised as ranging between long, thin points and short wide points, although this trend is not maintained for all samples. The dichotomy in eastern African point variability seen here could indicate the presence of at least two sub-regional traditions in point style throughout the Rift Valley system, potentially indicating a degree of cultural coherence and demographic stability through space and time. Obsidian sourcing studies at Prospect Farm found that, despite the site being very close to local raw material sources, exotic obsidian was utilised, leading van Baelen *et al.* (2019) to suggest the presence of long-distance trade networks through the Rift Valley. Cultural continuity and the maintenance of traditions have also been proposed from analyses of point technology at Nasera, Mumba and Magubike by Bushozi (2011); these assemblages were not studied in this analysis, but it would be interesting to explore how far the regionalisation of point-making traditions extended throughout the wider area.

In contrast, the metric data revealed several statistically significant differences within and between sites from these two sub-regions, as well as differences between assemblages from the same site. This indicates that form (shape and size) — rather than just shape — is more useful for differentiating between MSA points from different assemblages and is supported by differences in centroid size being significantly different between multiple assemblages with similarly shaped points. An additional benefit of including both metric and geometric morphometric data within the analysis is that thickness captures variability in the third dimension, an aspect of point form not accounted for in the outline. Thickness was found to have an independent significant relationship with geographic distance in the multiple matrix regressions, suggesting that points from assemblages further away from each other also have different point thicknesses. Thickness has been linked to the ballistics of the point and hafting, with thinner points allowing better penetration and thicker points having higher impact resistance and variability constrained by shaft configuration (White 2013); this is seen ethnographically with projectiles used to hunt small birds being broad and flat, which kill without penetrating the skin (Clark 1952; Hodder 1982). PC5, an axis of variance that characterises diversity in the shape of the hafted end, shows a significant relationship with thickness, supporting a potential link between base morphology and overall thickness that could be linked to functionality (White 2013). This may speak to the multifunctional nature of points, as has been proposed for the MSA (Douze *et al.* 2020), although functionality should also correlate with climatic variables to some extent as these are what condition the selective environment for tool manufacture (White 2013). Overall, this highlights the complex considerations required when using point typology without technological analysis or usewear studies to understand patterns of point manufacture and function, with further exploration ultimately needed with bigger samples from more assemblages.

Multiple matrix regressions found that point shape diversity between assemblages can be explained by the distance between them through time and space and in relation to variation in environments, particularly precipitation. These relationships can be further explored through individual regressions to better understand the nature and direction of the relationship (Figure 5). The results show that assemblages that differ in terms of point elongation tend to be found at further distances and in different chronological periods, with wider, shorter morphologies found in older contexts and/or at lower latitudes (Figure 5a–b). Wider points also tend to be associated with higher precipitation environments (Figure 5c). The negative coefficient for precipitation in the multiple matrix regression for PC1 and the final model suggests that, as points get more similar, the precipitation values they experience diverge. This is captured by the shape of the data in Figure 5c — variance between the points along the y-axis (precipitation) increases as variance between the points along the x-axis (PC1) decreases. This could suggest that higher precipitation environments allow for a wider variety of point shapes whereas those with relatively little rainfall act as a constraint on point shape. Because lower precipitation environments generally have fewer resources available, standardising point style may mitigate resource risk by ensuring that both the functionality of the tool is maximised and/or that different individuals within a group network can use it if it is intended to be traded (Wiessner 1977, 1982, 1983, 1985). More open xerophytic landscapes likely required thin, aerodynamic points for projecting across large distances, whilst wetter tropical landscapes tended to exhibit more variable tree-cover due to interannual variation in precipitation affecting leaf, flower, fruit and seed production (Boyle *et al.* 2020). In these contexts, points may have been less constrained by aerodynamics due to the ability to procure prey from close proximity. They may thus have

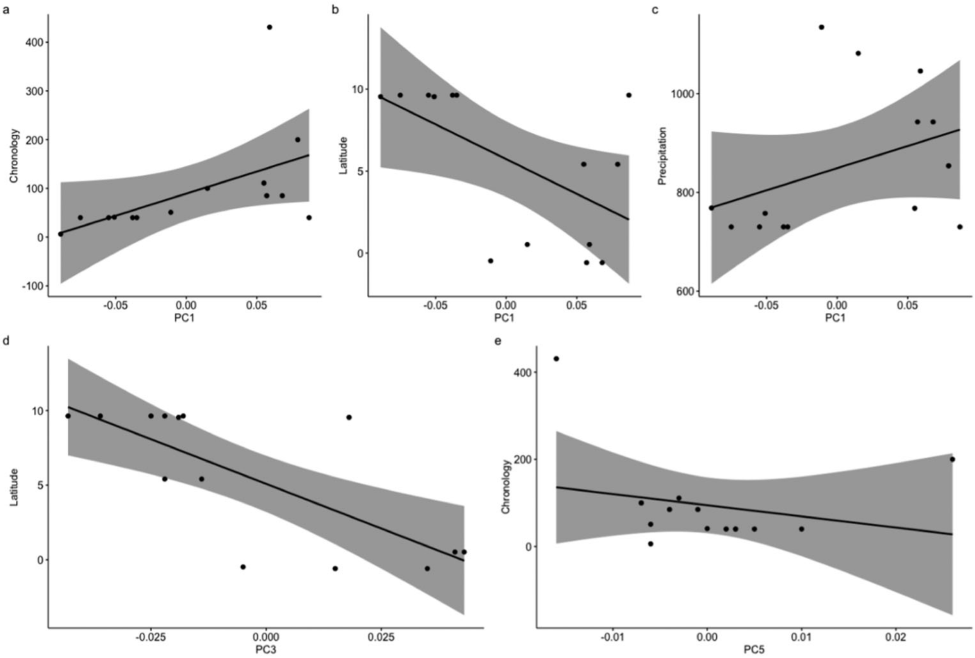

Figure 5. Regressions of principal components 1, 3 and 5 against chronology, latitude and precipitation according to which demonstrated independent relationships in the multiple matrix regression (see Table 4). 95% confidence intervals have been highlighted in grey.

been functional in a wider variety of tasks. Variable ecologies across Africa may also explain why points are rare from some MSA assemblages, particularly those found today in deciduous forest zones, such as Mumbwa Cave, Zambia (Barham *et al.* 2000). Assemblages that demonstrate diversity in patterns of tip narrowing (PC3) tend to be further apart in space, with points at lower latitudes appearing more triangular with acute tips (Figure 5d), a trend first noted by Clark (1988). Figure 5e highlights that diamond-shaped points (i.e. those with acute tips and convexity in the proximal end) tend to be found in younger contexts, although the correlation is not strong.

Together, these results indicate that a large proportion of the diversity in eastern African MSA points can be explained by null models of isolation by distance, time and environments. Cultural transmission tends to occur between groups that are proximal in time and space through interaction, structuring behavioural evolution as a result of copying and learning (Shennan 2020). Independent significant relationships between point shapes and precipitation also indicate a potential role in environmentally mediated convergence driving point shape variability, with certain point styles potentially representing adaptive responses to different palaeoecological contexts. The effects of temperature and rainfall on the ecosystem are difficult to disentangle, although precipitation has been found to profoundly impact food availability in the tropics due to the effects of rainfall on plant phenology, with major repercussions for fauna, foraging behaviour and reproductive and population growth rates (Boyle *et al.* 2020). On a global scale, Torrence (2001) predicts that in tropical environments that are less affected by seasonality more generalised tools used for hunting a variety of animals should prevail, compared to higher latitude environments where specialised forms that minimise risk due to shorter periods of game availability are observed. Applying these hypotheses to the African MSA, point shape, size and frequency could all be seen as adaptive to variable precipitation regimes that affect the range of prey available and thus the type of delivery system(s) adopted. For example, in South Africa, Still Bay bifacial points have been proposed to have been designed to be multi-functional and to economise raw material, factors that may have been useful in unpredictable and variable ecological zones (McCall and Thomas 2012). Additionally, bifacial lanceolate points found in Lupemban assemblages in Central Africa have been suggested to represent a rainforest adaptation to wood-working (Taylor 2022). Nubian Levallois points, first characterised in northern Africa (Groucutt 2020) and since also found in southern Africa (Will *et al.* 2015), may reflect adaptation within arid settings, resulting in convergent evolution between spatially disparate populations.

Our results indicate that even within 'generic' MSA assemblages (i.e. those not assigned to a specific industry based on diagnostic tools) point shapes vary significantly, with some aspects of variance probably related to engagement with different environmental contexts. Yet it remains the case that eastern Africa does not possess clearly distinctive point styles of the kind seen in other regions of the continent. We propose that the 'generic' nature of the MSA in this region could be reflection of its equatorial position in combination with its unique topographic landscape, which together helped buffer hominin populations against the strongest effects of climatic change. Eastern Africa was likely a refugial zone within Pleistocene Africa (Blinkhorn *et al.* 2022; Niang *et al.* 2023), with low resource risk supporting the maintenance of human populations across extended time periods (Blome *et al.* 2012). Long distance transport of raw materials (Brooks *et al.* 2018; van Baelen *et al.* 2019), as well as the production of variable yet 'generic' pointed technology, indicates that eastern Africa likely maintained extensive population networks, the interconnectivity of which changed over time and space and in relation to ecological zones (Scerri *et al.* 2018; Will *et al.* 2019; Scerri and Will 2023). Mosaic ecotonal habitats within eastern Africa may have helped mediate the distribution, density and connectivity at a local scale, as seen in other large mammal species (Tryon *et al.* 2016). The signal of high variability from eastern Africa thus likely reflects smaller-scale adaptations and fluctuations in population size, density and structure (Basell 2008; Tryon and Faith 2013; Lahr and Foley 2016) while the underlying cultural consistency and its 'generic' nature (Groucutt *et al.* 2015; Thompson *et al.* 2018) is likely to be a consequence of its role as a refugium within the wider African continent. Another question remains as to whether certain forms of points can be considered more 'innovative' or 'complex' than others, as has been historically proposed for 'specific' MSA industries. Pointed tools are observed consistently throughout the MSA and is thus a (variably expressed) technological behaviour established early in the evolution of our species (Will *et al.* 2019; Scerri and Will 2023). We suggest that MSA points should be considered to have been an adaptative technological system that was a dynamic component of both the MSA subsistence and social behavioural repertoire, with the underlying cognitive capacity for more stylistic forms likely present in most (if not all) populations. The manufacture of 'generic' versus 'specific' MSA points was therefore perhaps contingent on the demographic and ecological contexts of populations inhabiting different areas within Africa.

Conclusion

Eastern African MSA points are highly differentiated in both shape and form, with null models of space, time and environment, as well as the effects of raw material and size, found to explain around 44% of the total variance in point shapes between assemblages. The magnitude of this result is difficult to assess in isolation; ultimately, comparative analyses performed on samples from other regions are required to evaluate whether 'generic' points show more or less autocorrelation than sequences with 'specific' points. In our sample, over 50% of the total variance relates to unexplained variance, which could represent aspects of cultural or stylistic diversity. Indeed, it is these arbitrary aspects of variance that we, as archaeologists, tend to be interested in capturing in analyses of cultural and behavioural evolution, such as those modelling inter-group dynamics and the evolution of cultural complexity, even as they may partly be obscured through the confounding effects of autocorrelation. We argue that null models of autocorrelation should be routinely applied in quantitative analyses as the baseline level of variation expected from any archaeological sample. Our research demonstrates that 'generic' MSA points demonstrate marked variability and that our multivariate methodology enables the dissection of those aspects of cultural diversity that are most informative for researching questions about past behaviour.

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Notes on contributors

Lucy Timbrell is a Postdoctoral Research Fellow at the Max Planck Institute of Geoanthropology, Germany, and the Department of Archaeology, Classics and Egyptology, University of Liverpool, United Kingdom. She completed her PhD at the University of Liverpool in 2023 exploring population dynamics among Middle Stone Age populations in eastern Africa. She uses geometric morphometrics, eco-cultural niche modelling and GIS, among other quantitative approaches, to investigate the articulation of material culture and palaeoenvironments in both Africa and Europe.

Behailu Habte is a Curator of Prehistoric Collections and Archaeologist at the National Museum of Ethiopia in Addis Ababa, Ethiopia. He completed his PhD at the University of Toulouse-Jean Jaures, France on the lithic technology of the Later Stone Age in the Horn of Africa. He is a lithic technology specialist, with interests in early human technical behaviour, subsistence economy and land use patterns in eastern Africa.

Yosef Tefera is a Curator of Prehistoric Collections and Archaeologist at the National Museum of Ethiopia in Addis Ababa, Ethiopia. He completed his studies at Addis Ababa University and has interests in lithic technological behaviour during the Middle and Later Stone Ages in eastern Africa.

Christine Maroma is a Research Technologist in the Department of Archaeology in the National Museums of Kenya in Nairobi, Kenya. She is an expert on lithic technology and the archaeology of eastern Africa.

Emmanuel Ndiema is the Head of Archaeology at the National Museums of Kenya in Nairobi, Kenya. He is also a Research Associate in the Department of Archaeology at the Max Planck Institute of Geoanthropology in Germany. He completed his PhD at Rutgers University in New Jersey in the United States of America in 2011 exploring mobility and subsistence patterns among Mid-Holocene pastoralists in northern Kenya. His research investigates cultural responses to climatic variability, and he has been involved with many projects focused on the archaeology of eastern Africa, ranging from the Middle Pleistocene to the Holocene.

Kimberly Plomp is a bioarchaeologist and Faculty Member in the School of Archaeology at the University of the Philippines Diliman, Philippines. She completed her PhD at Durham University in the United Kingdom in 2013 quantifying palaeopathology using geometric morphometrics. She uses geometric morphometrics to investigate skeletal variation of both human and non-human primates.

James Blinkhorn is a Senior Researcher in the Human Palaeosystems Group at the Max Planck Institute of Geoanthropology, Germany. He is also an Affiliated Scientist in the Department of Geography, Royal Holloway, University of London, United Kingdom. His research focuses on human-environment interactions and stone tool analyses, using spatial and computational methods to examine relationships between behavioural innovation, biological evolution, and environmental change.

Matt Grove is a Professor in Evolutionary Anthropology in the Department of Archaeology, Classics and Egyptology at the University of Liverpool. His research interests in the Middle Stone Age of Eastern Africa, the effects of palaeoclimatic change and variability on hominin evolution and dispersal and developing new quantitative and computational methods for studying the archaeological record.

ORCID

Lucy Timbrell http://orcid.org/0000-0003-1229-554X
Behailu Habte http://orcid.org/0000-0001-8134-7281
Emmanuel Ndiema http://orcid.org/0000-0002-1335-2924
Kimberly Plomp http://orcid.org/0000-0002-9932-5491
James Blinkhorn http://orcid.org/0000-0002-9399-5515
Matt Grove http://orcid.org/0000-0002-2293-8732

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