The structure of the Middle Stone Age of eastern Africa

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Abstract:

The Middle Stone Age (MSA) of eastern Africa has a long history of research and is accompanied by a rich fossil record, which, combined with its geographic location, have led it to play an important role in investigating the origins and expansions of *Homo sapiens*. Recent evidence has suggested an earlier appearance of our species, indicating a more mosaic origin of modern humans, highlighting the importance of regional and inter-regional patterning and bringing into question the role that eastern Africa has played. Previous evaluations of the eastern African MSA have identified substantial variability, only a small proportion of which is explained by chronology and geography. Here, we examine the structure of behavioural, temporal, geographic and environmental variability within and between sites across eastern Africa using a quantitative approach. The application of hierarchical clustering identifies enduring patterns of tool use and site location through the MSA as well as phases of significant behavioural diversification and colonisation of new landscapes, particularly notable during Marine Isotope Stage 5. As the quantity and detail of technological studies from individual sites in eastern Africa gathers pace, the structure of the MSA record highlighted here offers a roadmap for comparative studies.

Key Words: Middle Stone Age; eastern Africa; behavioural variability;

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1. Introduction

Currently, our understanding of the geography of modern human origins is in a state of flux. Until recently, the earliest fossil evidence for *Homo sapiens* was found in eastern Africa dating to ~195 thousand years ago (ka) associated with Middle Stone Age (MSA) technologies (McDougall et al., 2005). Renewed dating of fossil specimens from Jebel Irhoud, North Africa, now present significantly older evidence for the earliest *Homo sapiens* ca 300ka, broadly contemporaneous with the earliest evidence for MSA technologies across Africa (Hublin et al., 2017; Potts et al. 2018). This is supported by genetic studies from southern Africa which indicate the differentiation of modern human populations within the region at a similar time frame (Schlebusch et al., 2017). As a result, eastern Africa no longer presents a discrete source region for the origins of *Homo sapiens*. Nevertheless, due to its pivotal geographic location, eastern Africa remains a potential source region for modern human dispersals out of Africa, offering access to two key routes of expansion into Eurasia via the Bab al Mandeb strait to Arabia or the Nile Valley to the Levant (Groucutt et al., 2015; Lamb et al., 2018). Biological evidence (fossils; genetic studies) increasingly supports a pattern of geographically structured populations amongst early *Homo sapiens* in Africa (Scerri et al. 2018). As a result, eastern Africa may have played a central role mediating interaction between populations split between northern and southern Africa. However, the ability to resolve the nature and configuration of such population structures within Africa is restricted by the sparse fossil record, poor preservation of ancient DNA in the region and limited ability to extrapolate from contemporary populations. Examining the structure of behavioural records offers a complementary approach to understanding the nature of past population structures within Africa (Scerri et al., 2014). Here, we illuminate the structure and variability of MSA stone tool assemblages across eastern Africa using a rigorous quantitative approach, combining data from a newly collated, comprehensive database of stone tool typology and chronology with geographic and environmental datasets.

The MSA of eastern Africa, broadly spanning 30-300ka, has a substantial research history. Clark (1988) reviews the earlier history of research and offers an overview of MSA occupations of the region. Critically, he notes that although certain aspects of technology are commonplace, such as Levallois technology or retouched points, they vary across eastern Africa and no feature can be considered ubiquitous. Clark provided an innovative combination of descriptions of sites and stone tool assemblages from across the region with geographic, ecological and environmental maps to illustrate how behavioural diversity was grounded within a diverse physical environment. This perspective on regional variability remains as relevant as ever and has proved robust to the increasing chronological resolution that has since developed.

Two more recent syntheses of the eastern African MSA record have played important roles in establishing the nature of behavioural variability in the region. Twenty years after Clark's review, Basell (2008) presented a synthesis of chronometrically dated MSA assemblages accompanied by a qualitative overview of assemblage composition. This overview clearly illustrated the diversity of stone tool use, highlighting considerable overlap between assemblages, and again stressing the absence of any single *fossil directeur* of the eastern African MSA. Extending Clark's focus on the interactions between ecology and behaviour, Basell (2008) highlights the placement of MSA sites within ecotonal settings, permitting access to wooded ecologies, in contrast to the previously assumed central importance of savannahs. Furthermore, the roles of volcanism and tectonics are also recognised alongside patterns of climate change as affecting the habitability of the region and permitting the identification of potential regional refugia. In conclusion, Basell (2008) hypothesised that following contraction of MSA occupations during the high aridity of Marine Isotope Stage (MIS) 6, regional expansion and movement into new environments in MIS 5 corresponded with increased mobility and changes in stone tool use, promoted by climatic, volcanic and tectonic push and pull factors.

Tryon and Faith (2013) augment the description of patterns of stone tool technology with the introduction of a quantitative appraisal of the presence/absence of a range of artefact types. Again, descriptions of stone tool technologies broadly echo earlier suggestions for considerable diversity across eastern Africa within different artefact types and the absence of a single unifying type. Notably, these authors suggest that the lack of regionally distinct and derived typological traits is likely to hamper efforts to identify human expansions from the region. Tryon and Faith (2013) evaluated the presence and absence of a range of stone tool and other artefact types using correspondence analysis from dated assemblages, differentiating early (MIS 6 and earlier) from later (MIS 5 and later) assemblages. Alongside considerable overlap between early MSA and some later MSA assemblages, they identify a subset of later MSA assemblages that appear distinct, associated with the presence of blades and backed pieces, as well as beads, grindstones, ochre and anvils. These latter categories appear critical in resolving between earlier and later assemblages (Tryon and Faith 2013: Figure 4). In addition, Tryon and Faith (2013) demonstrated a weak but significant negative relationship between geographic distance and assemblage similarity, suggesting that geography does have some effect on the observed patterning. Whether this is due to geographic distance per se, or to habitat differences within the region, remains an open question.

These three reviews highlight a number of common themes in their appraisal of eastern African MSA sites, such as the lack of clear intra-regional structure in behaviour, the importance of ecotonal site locations, and the absence of regionally specific stone tool use. Typology remains a key means to evaluate variability across the breadth of the MSA record, although it is not entirely unproblematic. Not only have a wide range of terms been employed to describe stone tools in the MSA of eastern Africa over its extensive research history, but it is broadly acknowledged that significant technological diversity can exist within stone tool types. Elsewhere in Africa, where a comprehensive, technological study of stone tools across a wide area have been conducted within a single analytical system, it has been possible to resolve distinctive, regionalised patterns of behavioural variability within stone tool types (Scerri et al., 2014). To date, no such analysis has been undertaken in eastern Africa.

The use of a broad typological approach may somewhat limit the detail of insight into the precise nature of inter-assemblage relationships, but in advance of a fine-grained systematic appraisal of technological approaches, it provides the ability to objectively compare large numbers of sites and to elucidate generic patterns. Any quantitative archaeological analysis faces a trade-off between resolution at the assemblage scale and the number of assemblages that are available for inclusion. The presence / absence approach developed by Tryon and Faith (2013), and extended considerably below, sacrifices fine-scale resolution in favour of analysing the largest possible number of assemblages. This approach is particularly apposite for the eastern African MSA, as it has been established by numerous authors that there exist no 'typical' assemblages that fully characterise this region and period (such as the Aterian of North Africa or Howieson's Poort of South Africa [e.g. Clark 1988; Tryon & Faith 2013]). The goal of this paper is to build upon these previous syntheses of behavioural variability in the MSA of eastern Africa by extending the application of quantitative approaches. In particular, we aim to illuminate the structure of eastern African MSA behaviour, in terms of the typological composition of stone tool assemblages, the variability of site locations with regards to their geographic and environmental features, and how these change through time.

2. Datasets

A broad synthesis of published literature reporting MSA sites was undertaken to compose the dataset for the proposed analyses. Where possible, this involved consulting primary reports on stone tool assemblages, although in rare instances this was not possible. In order to produce as large a database as possible, typological data were also synthesised from secondary sources, principally Basell (2008) and Tryon and Faith (2013), and details of site locations were collected. Chronological data for the assemblages was also collated, but the presence of secure dating was not a prerogative for inclusion within the dataset.

Typological terminology used to report MSA assemblages from eastern Africa has varied considerably over the region's extensive research history. In part, this may have stemmed from theoretical differences underlying the methods and goals of stone tool analysis: whether types represent finished tools for either cultural or functional purposes, or whether they occur as points within a reduction continuum. Other factors include the introduction of formal definitions of key technological systems, such as Levallois methods (Boeda, 1994), post-dating the excavation and reporting of key sites. Finally, there is considerable variation in the level of detail available on MSA assemblages, ranging from very basic typologies simply indicating proportions of cores, flakes, tools and debris, to detailed technological descriptions resulting from chaine opératoire studies (e.g. Douze, 2012).

The goal here is not to present a new composite typology for studying eastern African MSA assemblages, but to homogenize methodologically diverse reports of stone tool assemblages into a single framework for analysis; this is essential for a thorough examination of the structure of behavioural diversity in the region. Rather than using the typology as an immutable representation of past behaviour, we use it to structure our analysis, and note that tensions within and between typological categorisations may offer profitable lines of future enquiry. Typologies reported frequently conflate reduction methods (e.g. blade production), artefact form (e.g. denticulate), and artefact function (e.g. chopper). This mixture is retained for this analysis for consistency with previous approaches and to enable evaluation of the breadth of MSA behaviour. An important caveat is that the identification and grouping of artefact types is contingent upon the level of resolution afforded by primary reports of stone tool assemblages. It is also important to acknowledge the potential role of raw material variability and flaking mechanics in structuring both past behaviour and the typologies employed by archaeologists studying the MSA of eastern Africa. Again, the ability to evaluate the impact of raw material variability upon stone tool use is constrained by the nature of primary reporting of assemblages and is beyond the scope of the present analysis.

An extensive review of the eastern African literature indicates that over 1000 discrete stone tool types have been reported; inevitably, some categories overlap, and many are closely comparable with one another. Preliminary categorisation aimed to standardise these types to the most common terms with minimal data loss, ensuring the use of terms employed by more than 2 separate authors and across more than 2 sites. In order to preserve information this required the splitting of some terms (e.g. “flakes and blades”) into more than one category (e.g. “flakes”, “blades”). Categories that were nearly ubiquitous (e.g. flakes; core; tool) were then removed as their widespread occurrence offers limited means to resolve patterns of behaviour within the analytical framework adopted. Similarly, some stone tool types (e.g. core management flakes) offer no useable information to resolve between alternate reduction technologies or uses and have been excluded from the analysis.

Secondary categorisation aimed to further standardise the use of terminology while limiting the levels of subsets within groups. For example, amongst heavy tools, artefacts may have been reported by a single type (e.g. pick) or include further technological data (e.g. bifacial pick). Similarly, many cores are simply described as Levallois cores, whereas others are described as bidirectional recurrent Levallois cores. In both cases the latter type is a subset of the former and has been subsumed into the more extensive category.

In rare instances, single artefacts could not be grouped meaningfully with other types or were best grouped with types that had already been removed (e.g. a single instance of a “basally modified retouched tool”) and were also excluded from the data set. Finally, cores, flakes and retouched pieces from particular technological types were combined, as the presence of one (e.g. a retouched Levallois point) suggests the presence of the other two (Levallois point core and Levallois points), and thus serves as an index of the wider technology. A total of twenty-six types were identified for use in the analysis and are described below. These broadly reflect but expand upon other recent, predominantly qualitative, syntheses (Basell 2008, Tryon & Faith 2013). Following the categorisation of typological terminology described above, only assemblages that preserved at least two different types were preserved in the data set for the analyses presented below (see Table SI.1 for a full list of sites and references). A total of 125 assemblages from 57 sites were identified.

2.1 Reduction technologies

Three types used in the analysis conflate combinations of core and flake types from the same technological systems. *Bipolar technologies* involve striking a core while placed on an anvil.

Core on Flake technologies exploit flakes as masses of stone for further debitage production, including Kombewa cores and flakes, where flaking is orientated along the original axis of percussion, leading to secondary flaking removing the original bulb of percussion. *Point technology* involves the production of triangular flakes, including pseudo-Levallois points. A further four types combine cores, flakes and retouched types from particular technological systems. *Blade technologies* focus upon the production of elongate flakes, typically at least twice as long as they are wide. Following Boeda (1994), Levallois technologies involve hierarchical shaping of core volumes and convexities to predetermine flake shapes. Here, we differentiate *Levallois Flake, Blade* and *Point* production. Although not all primary sources clearly differentiate Levallois and non-Levallois blade and point technologies, it is unclear from the literature whether this results from the analytical terms used or represents an actual absence of such artefact types. As all four types do occur in some assemblages, we do not conflate them here, recognising they may illuminate patterns of differentiation of reduction technologies that could be further bolstered by reappraisal of the original assemblages.

2.2 Core Technologies

In addition to those specified above, a number of discrete core reduction methods are included for analysis. Cores that exhibit a distinct platform, but lack other formal preparation are classified as *Platform Cores*, including Single, Multiple and Bidirectional forms. *Discoidal Cores* are centripetally flaked from a platform onto a peaked surface and appear as either unifacial or bifacial forms. Here, *Radial Cores* are used to group cores reported either as such or as prepared cores, as both indicate the use of prepared platforms to exploit centripetally flaked, relatively flat core surfaces. In some instances, this may overlap with modern definitions of Levallois flake cores, especially from older reports, although it is worth noting they are still reported as discrete types (e.g. Tryon et al., 2015).

2.3 Retouched Tools

Fourteen different forms of retouched pieces are included for analysis. Some methods of retouching are distinct and form types used in the analysis, such as *Burins*. The use of backing, or abrupt retouch, in the production of diverse *Microliths*, is a further example of a distinct method of retouch, and here different forms of microlithic tools (e.g. crescents, trapezoids) are not differentiated from one another. Bifacially retouched tools are frequently reported in eastern African MSA, and here *RT Bifacial* is used where no further detail regarding tool form is used (e.g. bifacial scraper or point). A number of retouched types are recognised based on tool form. *Retouched (RT) Points* (including unifacial and bifacial forms) have played a key role in the research history of the eastern African MSA, and are widespread, although not ubiquitous. *RT Knives* are often of similar sizes and shapes to retouched points in plan but are only retouched on one edge that is opposite a distinctly thicker edge. *Borers* incorporates all tool forms with a distinct drill-like bit, such as awls. *Scaled Pieces* are typically reported as retouched tools, and although the pattern of crushed retouch they preserve may reflect a distinctive use, it may reflect their production through bipolar reduction. The remaining four retouched types are some of the most common, being *Scrapers*, *Denticulates*, *Notches* and *Notched Tools* (i.e. notched scrapers or notched denticulates). While extensive typologies are reported, especially for scrapers, differences between these tool forms may reflect cultural preferences for particular shapes, their use for alternate tasks, or the accumulation of increasingly invasive retouching through an artefacts life history.

2.4 Heavy Tools

Five types comprise heavy tools represented at MSA eastern Africa sites; these are *Biface*, *Chopper*, *Handaxe*, *Pick* and *Large Cutting Tools (LCT)*. These types have typically been differentiated by their form, with the latter combining tools reported as *LCT* with informal heavy tools as well as tool types which were reported at very low incidence, including core axes and cleavers. In a similar manner to retouched tools, these types may also reflect reduction continua. *Choppers* and *LCT*s may have undergone more limited flaking than *Bifaces*. *Handaxes* typically refer to tear-drop shaped bifaces, whereas *Picks* may reflect one of these forms that has undergone considerably more extensive reduction or use.

2.5 Geography and Environments

Site locations were either collected as co-ordinates from the literature or, where necessary, georeferenced from maps (Table SI.1). Raw data used in the analyses includes SRTM DEM (Jarvis, A., H.I. Reuter, A. Nelson, 2008) data for altitude, and two bioclimatic variables (mean annual temperature, mean annual precipitation) for modern conditions (1970-2000; Hijmans et al., 2005), as well as modelled data for these variables for the Last Glacial Maximum (LGM) 21 ka (Braconnot et al., 2007) and the Last Interglacial (LIG) in MIS 5e (Otto-Bliesner et al., 2006). The physiographic landscape of eastern Africa is impacted by ongoing tectonic activity (see Chorowicz, 2005), that complicates the use of the modern landscape to directly characterise those of the past. However, the modern landscape remains the most suitable analogue to past geographic settings, with differences from past conditions partially mitigated by sampling across a 50km radius (see below). Equally, modelled past environmental conditions for the LGM and LIG are used to provide possible extremes of variability observed within a glacial-interglacial cycle and the impact this could have upon human populations, rather than used directly to represent specific conditions during the LIG and LGM.

3. Methods

Dissimilarity matrices and hierarchical clustering are employed to identify patterns of association between both assemblages and typological variables, as well as for spatial datasets, including geographic and environmental data. Dissimilarity (or distance) matrices are produced from pairwise comparisons of cases using an appropriate metric resulting in a measure of dissimilarity. Hierarchical clustering is a form of cluster analysis that iteratively merges cases into a group or splits a group into cases using a measure of closeness, with the results commonly presented in the form of a dendrogram. These are common forms of multivariate analysis, that are regularly described in both introductory and more advanced textbooks (e.g. Krzanowski, 2000; Manly & Alberto 2016). Two alternate metrics are used in calculating the dissimilarity matrices used and are described below. The complete linkage method was employed for hierarchical clustering in all instances, as it is the only method suitable for presence/absence data.

3.1 Behaviour

Jaccard's coefficient is used to calculate dissimilarity between cases of assemblages and lithic types, as it is optimised for analysing presence/absence data. This coefficient treats mutual presence of a particular type in two assemblages as evidence of similarity but gives no weight to mutual absence. The focus on occurrence rather than absence data is particularly suitable given the imperfect nature of archaeological sampling.

Two alternate approaches to hierarchical clustering were employed. Divisive clustering was undertaken with the assumption that all cases form part of a cohesive group, i.e. that the MSA reflects a shared behavioural background across the dataset. Each divisive step of the clustering algorithm maximises dissimilarity between cases until each assemblage is separated into an individual cluster. Divisive clustering was undertaken using the DIANA tool in the cluster package of R. In contrast, agglomerative clustering begins with the assumption that all cases are distinct, i.e. that there is no common MSA behavioural background across the dataset. Each agglomerative step minimizes dissimilarity between cases until a single group (i.e. the MSA) is formed. Agglomerative clustering was undertaken using the *hclust* tool in the stats package of R. These alternate approaches to clustering offer complementary information as to how behavioural diversity in the eastern African MSA is structured through time, space and with respect to environmental conditions.

3.2 Geography and Environments

Examining the diversity of site locations focuses upon a number of geographic and environmental parameters, identified above. In addition to altitude, a further geographic dataset representing the energetic consumption for a 50kg human walking within the landscape was created. The SRTM DEM was used to generate a slope raster in ArcGIS 10.3, which was then translated into a raster representing energy consumption in joules for crossing 1m at the different slopes encountered, producing an isotropic cost surface based upon results of energy consumption presented by Minnetti and colleagues (2015).

In order to understand the landscape in which sites are situated, rather than the individual sites alone, 50km radius buffers around the site were used to sample geographic and environmental datasets, informed by home range sizes from hunter-gather populations (Binford, 2001) and patterns of raw material use (Blegen, 2017; Faith et al., 2015). Individual raster datasets were created for each site buffer for the raster datasets and histogram data were collated using the Zonal Histogram tools in ArcGIS 10.3. Geographic, modern and MIS 5e environment data sets resulted in ~9000 cells of data for each site, while LGM data sets resulted in ~3000 cells of data for each site. The exported data were transformed from histogram data to probability distributions. Using the HistDAWass package (Irpino, 2017) in R, dissimilarity matrices were calculated using the L2 Wasserstein distance, which enables characterisation of the scale, skewness and kurtosis of histogram-based data. Hierarchical clustering of the dissimilarity matrices was then employed to examine grouping of sites according to geographic (SRTM DEM and energy consumption cost surface) and three environmental (modern, LGM, LIG) datasets using complete-linkage clustering algorithms.

3.3 Chronology

Chronological data is employed as an additional means to describe patterns of variability amongst behavioural, geographic and environmental datasets, focusing on change through time. Given the wide variety in reporting of ages for MSA assemblages in eastern Africa, and the variability of uncertainty associated with different methods, we confine discussion of chronology in the main text to Marine Isotope Stages. Assemblages are assigned to the MIS with the greatest overlap with reported age constraints from either directly dated assemblages, or those bracketed by overlying and underlying units. Where only minimum or maximum age brackets occur, they are assigned to the stage in which the date occurs. In some instances, undated assemblages have been ascribed to a particular MIS by previous studies based upon site geomorphology (Basell 2008; Tryon & Faith 2013), and these are included here. Marine Isotope Stages are used in the text as a shorthand to describe changing patterns of stone tool typology through time, as well as an index of climatic conditions, rather than as a definitive assessment of eastern African MSA chronology.

4. Results

Hierarchical clustering allows for the clustering of both stone tool types (based on how frequently they are co-present in different assemblages) and assemblages (based on how many tool types they share). Figure 2 shows a binary heatmap of presence and absence data for the 26 stone tool types in each of the 125 MSA assemblages for which data were collated. The results of the analyses described above are presented in three sections. Firstly, the results of clustering of the stone tool types are reported, illuminating which constellations of artefacts are commonly found in association with one another. Secondly, the results of clustering the assemblages are presented, illustrating patterns of similarity and difference in the combinations of artefact types present between assemblages. Thirdly, the results of clustering of geographic and environmental datasets will be presented to examine diversity in the landscapes occupied by eastern African MSA hominins, and correlations with behavioural clusters explored.

4.1 Stone Tool Types

Agglomerative clustering identifies three discrete basal clusters of stone tool types (AT1-3), whereas divisive clustering identifies four discrete basal clusters of stone tool types (DT1-4)(Figure 3). The largest clusters produced by either method (AT1 and DT1) share twelve of fifteen artefact types in common, structured into two (divisive) and three (agglomerative) sub-clusters. Both methods identify *Levallois Flake Technology*, *Blade Technology*, *Platform Cores*, *Discoidal Cores*, *Scrapers* and *RT Points* in one of these sub-clusters, and *Levallois Blade* and *Levallois Point Technology*, *Point Technology*, *Denticulates*, *Cores on Flakes*, and *Choppers* in a second sub-cluster. The third sub-cluster of AT1 is comprised of *Burins*, *Notched Tools* and *RT Knife*, which form the discrete basal cluster DT2 using the divisive approach. *Borers*, *Notches* and *LCT*'s augment the first subcluster of DT1, whereas using agglomerative methods they form part of AT2. Both agglomerative and divisive methods identify the association of *Bipolar Technology*, *Microliths*, *Radial Cores*, *RT Bifacial* and *Scaled Pieces* in discrete basal clusters AT2 and DT3. *Bifaces*, *Handaxes* and *Picks* are identified as discrete basal clusters by both agglomerative (AT3) and divisive (DT4) clustering methods.

4.2 Assemblages

Agglomerative clustering identifies seven discrete basal clusters of stone tool assemblages (A1-A7) while divisive clustering identifies eight separate groups (D1-D8)(Figure 4). No direct overlaps occur in the composition of the clusters identified by alternate methods, although the three members of A2 (Abdur_N_C_S; Garba3_S1; Karungu_GS) are augmented by a fourth site (Omo_KHS_gully) to form D8. Beyond this, numerous pairwise combinations of assemblages are identified by both methods leading to repeated partial overlaps in assemblage clusters identified by alternate methods. At some sites with multiple assemblages, including Koobi Fora, Naisiusiu, Nasera, Olorgesailie, Porc Epic and Prospect Farm, all assemblages form part of the same clusters identified using both clustering methods, although elsewhere, such as at Mumba, Mochena Borago, Lukenya Hill, Koné, alternate assemblages contribute to different clusters. The typological composition of each assemblage cluster is presented in Figure 5 and the most commonplace traits are described in Tables SI.2 and SI.3.

4.2.1 Distribution of assemblage clusters

The largest agglomerative and divisive clusters (A1 and D1) appear at sites that are widely distributed across eastern Africa, and a similar lack of spatial structuring is also apparent amongst the majority of the smaller clusters. Amongst agglomerative clusters, A3 is particularly notable for appearing in a concentration of sites in the Turkana Basin, supplemented by two sites from the northern rift valley and one from the southern rift. Amongst divisive clusters, D5 assemblages are only found in the northern rift. Although assemblages from cluster D7 do appear in both the Turkana Basin and northern rift, they are much more numerous in the southern rift.

4.2.2 Chronology

The earliest MSA assemblages date from MIS 9, appearing in two different clusters using both agglomerative (A7 and A1) and divisive (D6 and D7) methods. Amongst agglomerative clusters, A7 is notable for spanning MIS 9-2, with particular concentration of sites apparent from late MIS 5 to early MIS 3. The greatest diversity of agglomerative clusters appears in MIS 5, which is the only period when all seven are present, with five agglomerative clusters found in both MIS 7 and MIS 3. Of the seven agglomerative clusters, five appear in both the Middle and Late Pleistocene, with A2 only present during MIS 5, and A6 only apparent in the Late Pleistocene. A1 is notable as it includes the largest number of assemblages during the humid phases of MIS 7, 5 and 3.

No single divisive cluster is found in all Marine Isotope Stages, but both D6 and D7 first appear in MIS 9 and are represented in all subsequent stages, apart from MIS 6. While present in MIS 8, D1 comprises the largest number of assemblages in MIS 7 and in each stage of the Late Pleistocene. Amongst the smaller clusters, two (D4 and D8) are found in the Middle Pleistocene and MIS 5, but not are not apparent in the latter stages of the Late Pleistocene, whereas two clusters (D2 and D3) first appear in MIS 5 and are only found in the Late Pleistocene.

5. Sites

5.1 Geography

Six geographic clusters (G1-G6) are broadly delineated into higher (G1-3) and lower (G4-6) altitude groups (Figures 7 [left] and SI.2a; Table 1). Abdur (G6) is a unique environment, with particularly high cost of movement relating to the high slope of the region that spans the coastal plain to high-altitude hilly terrain. This makes it distinct from other sites located on or near coastal plains (G5), or those within the low altitude and broadly flat Turkana basin (G4). The three high altitude clusters exhibit distinct altitude ranges, the lowest of the three, G2, typically exhibiting a lower cost of movement than either G1 or G3.

Cluster	Description
G1	High Altitude (~1320-1720m)
G2	Middle Altitude (~1075-1320m)
G3	Highest Altitude (~1890-2340m)
G4	Low Altitude (~450-720m)
G5	Coastal (~150-200m)
G6	Near Coastal (~790m)

Table 1: Key characteristics of geographic clusters.

The three largest agglomerative assemblage clusters (A1, A4, A7) appear in the four major geographic clusters (G1-4) (Figure SI.2). While A7 appear evenly split amongst the middle and high altitudes of G1-3 and A4 predominately occurs in the high-altitude settings of G1, A1 is broadly split between the higher altitudes of G1 and G3 and the low altitudes at G4. The broadest range of agglomerative assemblage clusters is associated with the highest altitude contexts of G3, with six of seven clusters present. All but one assemblage from coastal contexts are associated with the smaller agglomerative assemblage clusters, namely A6, A5 and A2.

Seven difference divisive assemblage clusters are found associated with the middle and low altitude settings of G2 and G4, whereas six divisive assemblage clusters are found associated with the high-altitude settings of both G1 and G3. D7 and D1 appear in the most diverse range of geographic contexts, occurring in all four main geographic clusters, comprising the majority of assemblages associated with the middling altitudes of G2, as well as in one of the coastal groups (G5). D1 is notable for having the highest number of assemblages associated with both the high-altitude contexts of G1 and low altitude contexts of G4.

MSA sites in eastern Africa are most consistently found in higher altitude settings of G1, spanning MIS 9-2, and G3, spanning MIS 8-3. While the majority of occupations during MIS 9-8 relate to these upland contexts, the majority of assemblages in MIS 7 occur in the lowland contexts of G4. During MIS 5, occupation appears to be evenly split amongst the five largest clusters and marks the first evidence for occupation of both the coastlines (G5 and G6) as well as low latitude contexts (G2). Occupation in MIS 4 is concentrated in the highest altitudes of G3, whereas in MIS 3 this focus shifts to slightly lower contexts associated with G1.

5.2 Modern Environments

Five clusters are identified based on characteristics of mean annual precipitation and temperature, split between more seasonally variably hot and arid environments (E1 and E2) and less seasonal and more humid environments (E3-5) (Figure 7 [right]). E2 presents one extreme of environments in eastern Africa, comprising arid environments with less than 400mm annual rainfall, and mean annual temperatures ranging between 20-30°C. E1 comprises sites in semi-arid to sub-humid settings (400-800mm annual rainfall), that are slightly cooler than E2, but with mean annual temperatures mostly above 18°C. Amongst the remaining three clusters, E5 is distinct, presenting the other extreme of eastern African environments with very high levels of humidity of around 1500mm annual precipitation. The remaining two clusters exhibit similar temperature characteristics of 15-25°C, but are split between semi-humid (800-1000mm) and humid (1000-1200mm) precipitation regimes.

Cluster	Description
E1	450-750mm; >18°C
E2	<400mm; 20-30°C
E3	950-1185mm; 15-25°C
E4	800-940mm 15-25°C
E5	1500mm;

Table 2: Mean characteristics of environmental clusters.

The distribution of these groups is shown in Figure SI.3. Although many of the clusters appear widely distributed, elements of spatial structure are evident in the modern environmental characteristics of eastern African MSA sites. The most northerly sites in the region all fall within the arid group of clusters E1 and E2, and stand in stark contrast to the more humid habitats of the central Ethiopian rift, where sites form part of E3 and E4. A similar shift is observed with sites clustering around Lake Turkana form the major component of the most arid cluster, E2. A more mixed pattern can be observed in the Kenyan rift, with a greater frequency of sites from all three humid clusters, as well as closer overlap with semi-arid cluster E1.

Environmental clusters E1, E2 and E3 all include members from six of seven of the agglomerative assemblages. Three agglomerative assemblage clusters appear across the full suite of modern environmental clusters, with A1 assemblages appearing evenly split across E1-4, A7 assemblages appearing sparsely in E2 compared to other environments, while A5 assemblages are predominately found in E2.

At least one assemblage from each divisive assemblage cluster occurs in E2, with 7 divisive clusters present in E1, 6 clusters present in E3, with E4 split between five divisive assemblage clusters. Both D6 and D7 appear in all five environmental clusters, with D6 concentrated in the semi-arid habitats of E1, while D7 is concentrated in more humid environments of E3 and E4. D1 and D2 assemblages both appear fairly evenly split across the four major environmental clusters (E1-4).

The earliest MSA assemblages in eastern Africa are predominately found in either semi-arid (E1) or semi-humid environments (E4) during MIS 9 and 8. Indeed, the semi-humid habitats of E4 have been occupied in each MIS from MIS 9-2, including the only examples of occupation dating from MIS 6 and 4. Occupation of either wetter (E3) or drier (E2) habitats appears clustered in more humid stages of MIS 7, 5 and 3. While evidence for occupying the more humid settings of E3 during the Middle Pleistocene is restricted to a single site, the majority of MIS 7 occupations are associated with the arid settings of E2. In the Late Pleistocene, occupation appears fairly evenly distributed between E1, 3 and 4, with fewer sites appearing in arid E2.

5.4 Past Environments

5.4.1 Arid conditions

Cluster	Details
LGM1 – semi humid	12-20°C; 675-880mm
LGM2 – semi arid	13-22°C; 400-650mm
LGM3 - arid	17-26°C; 90-310mm
LGM4 - humid	11-19°C; 1000-1130mm

LGM5 – v humid	15-22°C; 1330-1530mm

Table 3: Mean characteristics of LGM environment clusters.

Using environmental conditions during the LGM as a proxy for drier and cooler phases in eastern Africa, five major clusters are identified, split in to two groups, with the first group of arid to semi-humid settings (LGM1-3) typically more seasonal than the second group of humid habitats (LGM4-5) (Figure 11 [left]). Amongst the first group, cluster 3 is distinct, and is composed of sites with extremely arid and hot environments. Clusters LGM1 and LGM2 share similar ranges of temperature and are split between semi-arid and semi-humid environments. Within the second group, sites in LGM5 exhibit greater humidity and warmer temperatures than LGM4. Although the relationship between more arid and more humid clusters has changed in comparison to modern conditions, limited change is observed within the distribution of the clusters themselves, suggesting a region-wide decrease in humidity rather than reorganisation of environmental conditions associated with more arid phases (Figure SI.4). For instance, little difference is seen in the distribution of the most arid sites, while the Kenyan rift remains a more environmentally diverse region, with sites from different LGM clusters appearing in closer proximity than seen in the Ethiopian rift.

Under peak glacial conditions, assemblages from all agglomerative assemblage clusters appear in highly arid and semi-arid settings (LGM2 and LGM3), with A5 assemblages predominantly associated with highly arid LGM3 environments. Semi-humid habitats (E1) are dominated by the presence of the three largest agglomerative assemblage clusters, A1, A4 and A7. Both A1 and A5 are notable for appearing in all five LGM clusters.

Turning to divisive assemblage clusters, at least one instance of each cluster is found in the arid contexts of LGM3, with seven of eight clusters present in semi-arid LGM2 contexts. The largest assemblage cluster (D1) is predominately found in the semi-arid and semi-humid clusters E1 and E2, a pattern shared with D2. Both D6 and D7 are found in a broad range of environmental settings, spanning LGM1-4, with the former more numerous in LGM2, and the latter occurring more frequently in LGM1, as well as three of five assemblages in LGM5 habitats.

The modelled environmental parameters for the LGM offer a bracket for past climatic variability during arid phases, but may also offer more suitable analogues for other glacial stages than either present conditions or modelled LIG environments. The earliest MSA sites are found associated with the semi-arid habitats of LGM2, which show some occupation in all MIS except for MIS 4. It is noteworthy that the most arid landscapes (LGM3) are only occupied during interglacial phases (MIS 7,5 and 3). While limited evidence is available for occupation of semi-humid environments (LGM1) in the Middle Pleistocene, this cluster is particularly populous in the Late Pleistocene, including all assemblages dating from MIS 4.

5.4.2 Humid Conditions

Cluster	Details
LIG1	14-25°C; 370-740mm
LIG2	22-28°C; 145-275mm
LIG3	14-25°C; 765-1005mm
LIG4	14-21°C; 1060-1350mm

Table 4: Mean characteristics of LIG environment clusters.

Using environmental conditions during the last interglacial (MIS 5e ~125ka) as a proxy for hot and humid phases in eastern Africa, four major clusters (LIG1-4) can be observed, principally split on differences of humidity into two pairwise groups (Figure 11 [right]). The first pairwise group comprises LIG1, with a broad range of humidity from semi-arid to sub humid and temperatures ranging between 15-25°C, and LIG2, which are hot (all but one >25°C) and arid. The second pairwise group exhibits a broadly similar range of mean annual temperatures, that also overlaps the range observed for LIG1, but exhibit greater humidity, with LIG4 showing greater humidity than LIG3.

Some changes in the distribution of clusters can be observed with respect to modern conditions (Figure SI.5). The most arid cluster (LIG2) is now predominately clustered within the Turkana basin, whereas semi-arid to sub-humid LIG1 is widely dispersed in the Kenyan Rift as well as appearing in the Horn region. Sites appearing in different clusters are again found in closer juxtaposition within the Kenyan Rift, whereas greater homogeneity is observed in the Ethiopian Rift.

Assemblages from all agglomerative assemblage clusters appear in the humid LIG3 cluster, with all but one assemblage cluster appearing in the most humid cluster (LIG4). The presence of assemblages in the most arid environments (LIG2) is typically sparse and concentrated in A3. The majority of assemblages in A4, A5 and A6 clusters occur in the semi-arid to sub-humid environments of LIG1, with assemblages from the largest clusters (A1, A7) evenly spread across LIG1, LIG3 and LIG4.

Amongst divisive assemblage clusters, seven out of eight clusters are represented in the semi-arid to sub-humid environments of LIG1 and the humid settings of LIG3, with six divisive assemblage clusters apparent in other environments (LIG2, LIG4). Within the largest assemblage cluster (D1), assemblages are relatively evenly spread between alternate environmental clusters, though least populous in LIG2. Clusters D4, D6 and D7 are found in all four LIG environmental clusters, with D6 occurring in greater numbers in LIG1, while the D7 appears more concentrated in LIG3.

The modelled environmental conditions of the Last Interglacial (MIS 5e) offer an alternate bracket for environmental conditions in eastern Africa to the LGM presented above, relating to humid phases, which may serve as suitable analogues for MIS 9, 7, 5, and 3. There is longstanding evidence for MSA occupation of the semi-arid to sub-humid environments of LIG1, spanning MIS 9 to MIS 2, which includes all known sites in MIS 9 as well as the largest proportion of sites from MIS 3. Occupations of the humid environments of LIG3 also span the Middle and Late Pleistocene, but are heavily concentrated in MIS 5, representing the majority of sites occupied during this stage, with sparse occurrences stretching between MIS 8 and 3. Concentrated occupation of the most arid environments of LIG2 occurs in MIS 7, with two sites occupied in MIS 5 and a single site in MIS 8 in these environments. MSA occupations are not seen in the most humid environments (LIG4) until the Late Pleistocene, appearing in MIS 5 and representing all but one assemblages in MIS 4.

6. Discussion

Through the use of hierarchical clustering, we have set out a detailed, quantitative appraisal of behavioural diversity in the MSA of eastern Africa, both with regards to the constellations of stone tool types used, and the landscape contexts in which they are found. Here, the focus has been to use clusters of stone tools, rather than individual artefact types, to describe patterns of behavioural variability. The use of both agglomerative and divisive approaches to hierarchical clustering of behavioural datasets offer two alternate perspectives on the structure of stone tool use of the MSA in eastern Africa. Divisive clustering starts from an assumption of homogeneity, and subsequently identifies the divisions within the dataset, with the top-level clusters used here marking the minimum number of divisions within the data. As a result, divisive clustering offers an approach to understand the structure of shared technological repertoires across the MSA of eastern Africa. Agglomerative clustering starts from an assumption of heterogeneity, and subsequently identifies bottom-up pairings within the dataset, until the top-level clusters used here are formed. The differential expression of shared technological repertoires in response to distinct geographic and environmental factors may therefore be best approached using agglomerative clustering.

6.1 Stone Tool Types

Both methods of clustering identify two common combinations of MSA behaviour in the largest stone tool type clusters (AT1; DT1), the first (a) including *RT Points, Scrapers, Blade technology, Levallois Flake Technology, Platform cores and Discoidal cores*, and the second (b) comprising *Levallois Blade and Levallois Point technologies, Core on Flake technologies, Point Technologies, Denticulates and Choppers*. Under divisive clustering, these groups form a single, large cluster which offers a concise identification of the most common, co-occurring features of MSA assemblages. When the frequency of their occurrence is taken into account (see heatmap), these results potentially indicate that (a) comprises the most widespread manifestation of MSA technology, whereas (b) presents the most common means to augment or diversify this technology.

Under both clustering methods, *Bipolar Tech and Microliths* form pairwise clusters, as do *Radial Cores and RT Bifacials*, and these four types group with *Scaled Pieces* to form a common cluster. While the common co-occurrence of *Bipolar Technology* and *Microliths* is widely noted, their association with alternate flaking and retouching methods that is identified here has not been similarly stressed in previous analyses.

Both approaches to clustering indicate that well defined heavy tool types - *Picks, Bifaces* and *Handaxes* - form a distinct group. This common grouping may be explained either as reflecting positions on a shared reduction continuum, or as relating to specific functional demands for diverse, specialised heavy tools. In contrast, the poorly defined heavy tool types - *LCT* and *Choppers* - appear embedded within more diverse stone tool clusters. The requirement for heavy tools within MSA assemblages appears widespread, but the need for more formalised tools may relate to distinct behaviours in response to specific functional demands. At an alternate end to the spectrum of stone tool types, smaller retouched tools types are distributed across these clusters rather than grouping together. If these are interpreted as positions along a reduction continuum, then it appears retouched tools with differing use life histories are associated with differing constellations of other lithic technologies, which could be a result of practical factors, such as distance from raw material resources, or functional or stylistic constraints.

The most noticeable difference between clustering approaches relates to the associations of *Burins, Notched Tools* and *RT Knives* as a discrete subgroup on one hand, and *Borers, Notches* and *LCT*'s as a distinct subgroup on the other. *Burins, Notched Tools* and *RT Knives* form a discrete basal cluster under a divisive approach, suggesting they represent distinctive strategies amongst MSA technologies, whereas their association with AT1 under an agglomerative approach indicates that they are frequently deployed alongside the most commonplace MSA stone tool types. Likewise, the inclusion of *Borers, Notches* and *LCT*'s in DT1 suggests they are a consistent feature of the most common and widespread manifestation of MSA stone tool technologies, but their separation from AT1 may indicate that in practice they are less commonplace or occur in distinct behavioural contexts.

6.2 Assemblages

Seven major clusters were identified by agglomerative clustering. This bottom-up approach to identifying common patterns of behaviour identifies one cluster (A1) which comprises ~37% of all assemblages, suggesting widespread, common practices in using different stone tool technologies. Although no single tool type is shared amongst all assemblages in the cluster, *Levallois Flake Technology*, *Scrapers* and *RT Points* are all abundant. Similarly, the second largest cluster (A7) has no single ubiquitous stone tool types amongst all members, but *Levallois Flake* and *Levallois Blade Technologies* occur in high frequencies. Amongst the smaller clusters, *Handaxes* (A2), *Scrapers* (A3), *Platform Cores* (A4), *RT Points* (A5) and *Microliths* (A6) are found amongst all members of their respective clusters. Notably, even the smallest agglomerative clusters are comprised of tool types spread across the agglomerative tool type clusters, rather than being restricted to a single group.

Under divisive clustering the smallest number of clusters that MSA assemblages can be divided into is eight. Amongst these, four large clusters comprise the majority of assemblages (D1, D2, D6 and D7), and offer a characterisation of the most common modalities of MSA behaviour, whereas the four smaller clusters (n<10 assemblages) highlight more uncommon combinations of stone tool technologies. No single tool type appears in all assemblages in the largest cluster (D1), although *Scrapers*, *Levallois Flake Technologies* and *RT Points* appear in over 90% of these assemblages. Members of D2 and D6 all include scrapers, with distinct patterns of both other stone tool types present and their frequency. *Levallois Flake Technology* is ubiquitous in D7, but other tool types are present in low frequencies. Amongst the smaller clusters, D4 is notable for having three tools types, *Levallois Flake Technology*, *Blade Technology* and *Scrapers* in all assemblages, whereas other clusters are unified by the presence of *Microliths* (D3), *Bifaces* (D5) and *Handaxes* (D8). In a similar manner to the agglomerative clusters, divisive assemblage clusters comprise tool types that are spread across the divisive tool clusters.

Subtle variation in the constellation of artefact occurrence that define the different assemblage clusters and their members occurs between the two methods that precludes easy, direct comparisons. As above, the clusters identified through divisive methods perhaps best characterise the broad groups of technological practice, whereas agglomerative methods identify groups with distinct expressions of varied technological practices. A number of assemblages consistently cluster together under both methods, with 28 assemblages shared by the largest agglomerative (A1) and divisive (D1) assemblage clusters. In a similar manner, 8 of 10 assemblages in A3 are found together in D2, while 12 of 21 assemblages in A4 occur together in D1, and three quarters of assemblages in D4 occur together in A7. While multiple assemblages from single sites often cluster together under one method, a more limited number of sites have multiple assemblages that cluster together consistently under both methods, namely Koimilot (Kapthurin Formation), Koobi Fora, Naisiusiu, Nasera, Olorgesailie, Porc Epic and Prospect Farm.

The methods used here do not neatly identify individual stone tool types, or even combinations of tool types, that are ubiquitous across all assemblages, supporting previous assessments that the MSA is a polythetic group, lacking hard and fast rules to ascribe group membership. Instead, the results demonstrate that stone tool assemblages typically contain artefacts spread across clusters of commonly co-occurring stone tool types, but rarely express all the same elements. Similarly, the use of clustering has enabled quantitative assessment, from a wider range of sites and more numerous stone tool variables, of qualitative appraisals of patterns of spatial variability, suggesting little intra-regional variability.

6.3 Sites

Clustering using geographic as well as modern and modelled past climate data sets readily identify structure both within these data, and with respect to their distribution. Amongst the variables analysed, gross differences in altitude and precipitation present the main differences between clusters formed, with energy expenditure and annual temperature overlapping considerably between groups and presenting more subtle modulation to cluster formation. Notably, both precipitation and altitude have tangible impacts upon the make-up, distribution and seasonality of both faunal and floral populations (Siepielski et al 2017; Rosenzweig 1995).

Across datasets, the Kenyan rift presents the most heterogeneous habitats for MSA sites. Sites within the region fall in all three of the higher altitude clusters identified by analysing geographic variables, yet for environmental datasets, sites in the Kenyan rift occur across major divisions of clusters, such that even with the expansion of arid conditions, modelled for the LGM, a balance of arid to humid habitats are found. In contrast, broad latitudinal banding of habitats can be noted in site contexts from the Turkana basin and through the Ethiopian rift. The Turkana basin, presenting low-altitude contexts which consistently present the hottest, most arid site environments, presents a clear break in the landscape structure of eastern Africa, separating the mountainous and humid Kenyan and Ethiopian Rift. To the north, high altitude site contexts stretch through the Ethiopian Rift and the Horn, separating the northernmost lower altitude sites from the Turkana basin. Similarly, the sites in the middle Ethiopian Rift experience higher levels of humidity either than the Turkana basin sites to the south, or the

Horn and lowland sites to the north. As well as their distinct topographic setting on the Kenyan coast, Panga ya Saidi and Mtongwe repeatedly fall within more humid environmental clusters, which under some conditions diverge from sites in the Kenyan Rift at a comparable latitude. Similarly, the environmental characteristics of Nyara River, the southernmost site under consideration here, frequently stand in contrast to the rest of eastern Africa. These three sites all fall within more heavily forested regions today, and persistent humidity under past conditions may have perpetuated this distinction from the majority of eastern African MSA site habitats.

Only limited evidence for distinct spatial structure amongst stone tool assemblages in MSA eastern Africa is apparent. This may well reflect the influence of the mosaic geographic and environmental make-up of the region, with both considerable distances occurring between areas presenting similar habitats, such as in higher altitude areas of the Kenyan and Ethiopian Rift, as well as distinctly different landscapes occurring in relative proximity in the former. Similarly, no clear-cut patterns of certain assemblage clusters associating solely with single geographic or environmental site clusters were identified. Rather, patterns of emphasis, instead of exclusivity, are observed in associations between the two. Although certain packages of stone tools may have been most frequently used in some environments, the results here support scenarios in which they were not bound to those environments.

6.4 Chronology

Larger numbers of assemblages appear in interglacial stages (MIS 9,7,5 and 3), with warmer and more humid conditions potentially favouring both population growth and geographical expansion across the eastern African landscape. Whilst there may be a taphonomic component to this pattern, it is not simply a chronological preservation bias: for example, fewer sites are documented for the later MIS 4 than for the earlier MIS 5. Furthermore, the increase in numbers of sites in humid periods is accompanied by correlated increases in both the variety of tool forms present and the range of environments inhabited. Figure 9 demonstrates this geographical expansion, whilst Figures 10, 12, and 13 show that a wider range of environments is inhabited during MIS 5 and MIS 3 in particular, regardless of which environmental dataset is employed for reconstruction. MIS 5 is shown to be the most varied stage in terms of technology, geography, and environments inhabited; indeed, this is the only stage in which all of the 26 tool types are present. Sites during MIS 5 also demonstrate an increased habitation of coastal areas and a spread into mid-altitude areas. Collectively, these results support earlier suggestions that during humid stages hominin populations expanded into a broader variety of geographical regions, encountered a broader array of environments, and produced lithic assemblages of more diverse composition (e.g. Basell 2008).

Focusing on more archaeologically abundant phases, MIS 7, 5, and 3, there are a limited number of important chronological patterns in the tool forms present. Of the 16 types that are recorded in *all* of these stages, some steadily increase through time (i.e. the proportion of assemblages in which they are present follows a pattern showing MIS7<MIS5<MIS3). These types include *Blade Technology*, *Radial Cores*, *Notched Tools*, and *Bipolar Technology*. Types that decline include an associated group of *Levallois Flake* and *Levallois Blade Technology*, and *Discoidal Cores*, as well as *LCTs*, *Point Technology*, *Denticulates*, and *RT Knives*. Some of these types are closely associated in the dendrograms of Figure 3, whilst others are more distantly related. It remains a likely, therefore, that the gradual replacement of older tool forms by newer technologies is due to a complex interaction of reduction method and function, as well as the need to deal with changes in the resources encountered in an increasing variety of habitats.

Investigating the appearance of the largest assemblage clusters with respect to geographic and modern environmental clusters through time highlights a number of familiar patterns. In particular these are (1) continuity of using particular clusters of behaviour through time within the same geographic and environmental contexts, and (2) expanding the use of existing behavioural clusters in new contexts under favourable climates. Rarely do assemblage groups appear in very different settings (e.g. both extreme arid and humid) outside of interglacial phases, but overall these are patterns of emphasis rather than exclusivity. Refining our knowledge of spatial, environmental, and behavioural distinctions through time will remain vitally important to establishing how strong these patterns are, and where informative exceptions to them occur.

7. Conclusions

The Middle Stone Age of eastern Africa exhibits a diverse range of behaviour, in terms of the stone tools used by past populations and the geographic and environmental contexts which they inhabited. Through the application of a quantitative approach, we have been able to explore behavioural variability in greater detail than ever before and set out how this diversity is structured in time, space and across environments. Hierarchical clustering is an ideal method to employ to examine complex patterns of presence and absence across multiple, though at times sparse, typological variables. Importantly, adopting this approach has enabled us to effectively integrate data from sites that have been overlooked from previous, qualitative assessments, and especially those that lack clear chronometric control. The synthesis we present is also unique in the means of integrating data regarding the geographic and environmental contexts of the sites, and particularly for evaluating the variability of the wider landscapes surrounding sites. Combining these complementary approaches has enabled us to identify new patterns in the structure of behavioural variability of the eastern African MSA.

The typology employed here is not presented as an authoritative description of MSA stone tool technology but is used as a means to evaluate patterns of variability. It is noteworthy that both top-down (divisive) and bottom-up (agglomerative) methods of identifying clusters of co-occurring stone tool types identify one major cluster with two common, distinct components, from a range of common pair-wise associations. This offers some insight into what may count as a 'classic' MSA repertoire, with the introduction of additional elements resulting from different interactions with the environment as well as patterns of cultural transmission through time and across space. These findings may be consolidated upon further by refining the typology employed; such research will necessitate renewed analyses of existing assemblages where possible, to differentiate, for example, preferential from recurrent Levallois technologies.

Engaging with the breadth of MSA data that is available exhibits how varied constellations of stone tools were used to occupy a variety of geographic and environmental contexts. Typically, we identified patterns of emphasis, rather than exclusivity, both for the configuration of stone tools found together and where they have been used, offering support to qualitative approaches that have struggled to identify clear patterns. Nevertheless, this quantitative approach has been able to clarify a number of trends, particularly with respect to changes through time. The use of some constellations of stone tools and occupation of some landscape contexts appear to span most of the timeframe of the MSA, indicative of enduring behavioural adaptations, and potentially highlighting refugia for periods of enhanced climatic stress. Previous studies have split the MSA into early (MIS6 and older) and late (MIS5 and later) components (e.g. Tryon & Faith 2013), emphasising the appearance of new elements of behaviour in MIS 5. Rather than seeing a shift from early to late MSA behaviour, we have illuminated that MIS5 is a phase in which Middle Pleistocene MSA behaviours continue to occur but are significantly augmented with new combinations of stone tools appearing alongside the colonisation of significantly different landscapes that are characteristic of the Late Pleistocene. Further, targeted study is required to identify whether any particular stone tool technologies offered different functionality that enabled such diversification, and the results presented here can be significantly refined in the future by the inclusion of additional technological data.

This study illustrates the importance of combining archaeological assemblage data with information on the geographic, topographic, and environmental differences between the locations from which those assemblages are recovered. Only with more comprehensive data of this kind can we begin to link archaeological patterns with their potential abiotic causes. It is clear from the analyses above that there do exist patterns of differences between sites, and that there are partial explanations of such differences to be found in more detailed considerations of chronology, geography, and various elements of the local environmental setting. Environments inevitably change both across space and through time, and it is therefore essential to consider all these components simultaneously if we are to arrive at a comprehensive understanding of the archaeological record. It is also clear from the analyses reported here that there is much unexplained variation within the MSA of eastern Africa. Much of this no doubt arises from the stochastic nature of human behaviour and may relate both to individual differences and to the patterns of contact and conflict between subpopulations that were almost certainly isolated, both genetically and culturally, for long periods during the later Middle and Late Pleistocene.

It is now apparent that considerable chronological overlap occurs between eastern Africa's MSA industries with both the preceding Late Acheulean (e.g. Mieso dating to ~212ka [de la Torre et al. 2014]) and the succeeding Later Stone Age (e.g. Panga ya Saidi dating from 67ka [Shipton et al. 2018]). Beyond changes in emphasis in typological inventories, two key, inter-related elements associated with both major transitions in eastern African prehistory are raw material choice and artefact size. Due to the availability of comparable data, it has not been possible to examine these features as potential contributing factors to changing constellations of stone tool types. Similarly, to engage with the breadth of MSA assemblages in eastern Africa, it has not been feasible to examine varying constellations of artefact typology relating to the nature of different site types to explore, for instance, differences between logistical foraging compared to residential sites. Both offer potential avenues to extend the application of the quantitative analyses that are presented here.

Research into both the genetic and cultural foundations of *Homo sapiens* populations will continue to add to the debate concerning the patterns of material culture observed here, and in archaeological contexts from elsewhere in Africa and beyond. Analyses of the kind reported above, however, enable us to formulate questions regarding contact and isolation between groups that may be particularly amenable to future analyses of genetic and cultural transmission. For example, these analyses demonstrate that many tool forms – borers, LCTs, Levallois blade and point technologies, notched tools, and retouched knives – are *always* present to some degree in the humid Marine Isotope Stages in eastern Africa, and yet they are *never* present in the drier glacial stages. With various taphonomic caveats accepted, we can ask whether such technologies are reinvented during the geographic and demographic expansions associated with each humid stage, or whether they remain as unexpressed elements of the repertoire throughout dry stages when, for reasons as yet unclear, they are never physically realised. Similarly, Figures 8 and 9 establish geographic and environmental clusters that are inhabited throughout the period studied here, and such refugial areas should contain both the minimal distillation of MSA technology required for survival through arid periods and the core populations from which subsequent expansions result. There is therefore likely to be a close relationship between the smaller populations that survive less hospitable stages and the contraction of technological diversity found here among assemblages from MIS 8, 6, and 4. This relationship merits further study by archaeologists, but also by geneticists and researchers working on the dynamics of cultural evolution in fluctuating environments.

Acknowledgements:

This research has been supported by the Natural Environment Research Council as part of Grant: NE/K014560/1, "A 500,000-year environmental record from Chew Bahir, south Ethiopia: testing hypotheses of climate-driven human evolution, innovation, and dispersal", which forms part of the Hominin Sites and Paleolake Drilling Project. We thank two anonymous reviewers and the editor for their thoughtful comments that have helped to improve the presentation of this research.

The authors declare no competing interests.

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Figure Captions:

Figure 1: Map illustrating the distribution of key sites and locations mentioned in the text on an SRTM digital elevation model (Jarvis et al. 2008).

Figure 2: Binary heatmap of presence (black) and absence (grey) of twenty-six stone tool types recorded in 125 eastern African MSA assemblages.

Figure 3: Dendrograms illustrating hierarchical clustering of stone tool type variables amongst eastern African MSA sites using (left) agglomerative and (right) divisive approaches.

Figure 4: Dendrograms illustrating hierarchical clustering of stone tool assemblages amongst eastern African MSA sites using (left) agglomerative and (right) divisive approaches.

Figure 5: Heatmaps illustrating percentage presence of artefact types within groups identified by agglomerative (top) and divisive (bottom) clustering ranging from 100% (red) to 0% (white).

Figure 6: Jitter plot illustrating the number of assemblages in each agglomerative cluster found within each Marine Isotope Stage.

Figure 7: Jitter plot illustrating the number of assemblages in each adivisive assemblage cluster found within each Marine Isotope Stage.

Figure 8: Dendrograms illustrating hierarchical clustering of eastern African MSA sites based upon geographic characteristics (altitude and energy)(left), and modern environments

(mean annual temperature and precipitation)(right) within a 50km radius of site locations.

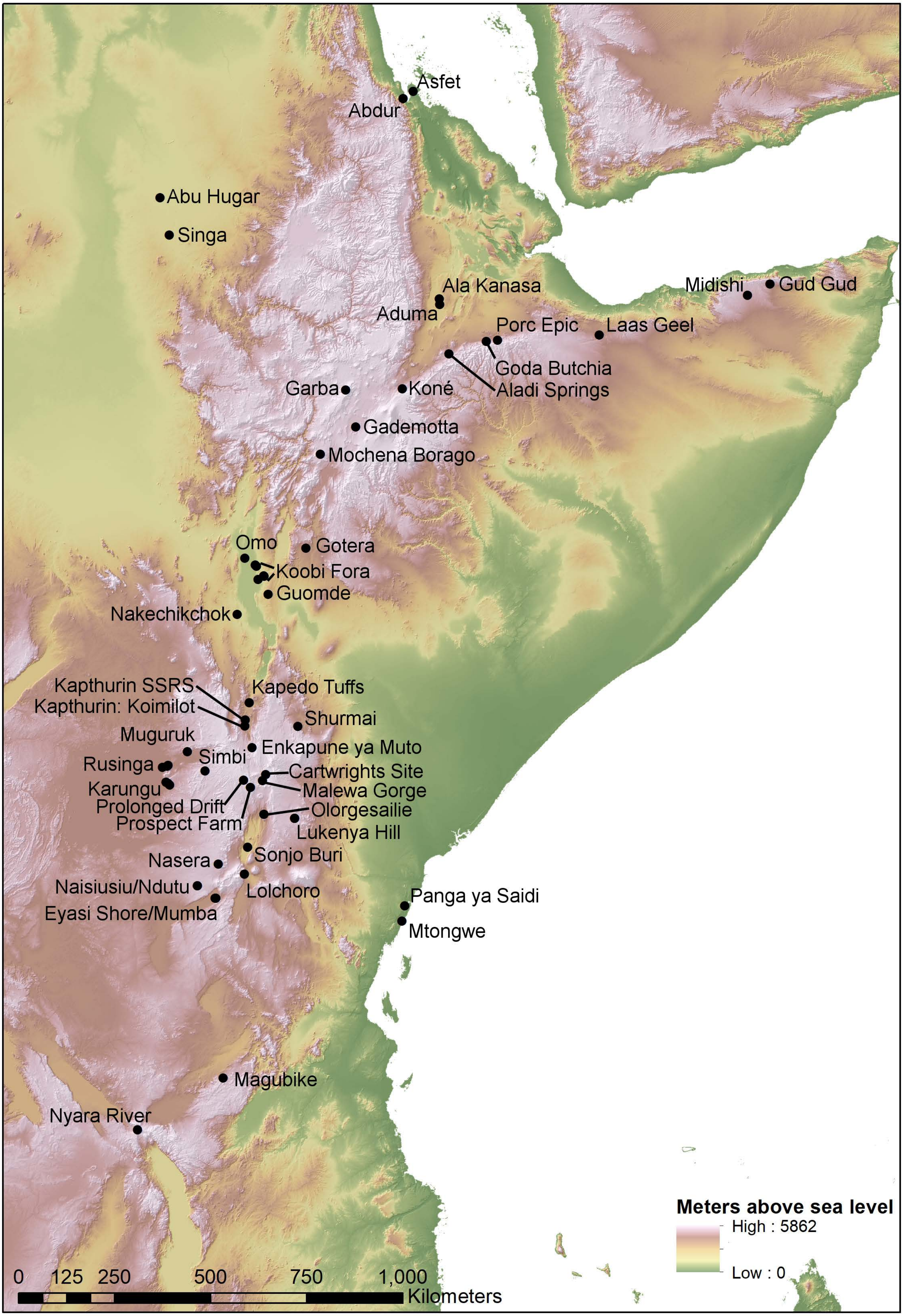
Figure 9: Jitter Plot illustrating the occupation of alternate geographic clusters (G1-6) split between Marine Isotope Stages, with long term continuity of occupation evident in G1 and G3, and significant expansion observable in MIS 5.

Figure 10: Jitter plot illustrating occupation of alternate modern environmental clusters (E1-5) split between Marine Isotope Stages, with long-term continuity of occupation evident in E4, pulsed occupations of E2 in odd-numbered stages (7,5,3), and expansions into new environments in MIS 5 and 3.

Figure 11: Dendrograms illustrating hierarchical clustering of eastern African MSA sites based upon modelled environmental parameters (mean annual temperature and precipitation) for the Last Glacial Maximum (21ka) as a proxy for arid conditions (left) and for the last interglacial (MIS5e) as a proxy for humid conditions (right).

Figure 12: Jitter plot illustrating occupation of alternate arid environmental clusters (LGM1-5) split between Marine Isotope Stages. Although repeated occupations of LGM2 and LGM3 are observed throughout the MSA of eastern Africa, only LGM1 preserves evidence for occupation during MIS4.

Figure 13: Jitter plot illustrating occupation of alternate humid environment clusters (LIG1-4) split between Marine Isotope Stages. Both LIG1 and LIG3 indicate occupation within both the Middle and Late Pleistocene. Occupation of LIG2 and LIG4 overlaps during MIS 5 but are otherwise split between the Middle and Late Pleistocene respectively.



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Gademotta
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Kapedo Tuffs
Shurmai
Muguruk
Simbi
Enkapune ya Muto
Rusinga
Cartwrights Site
Karungu
Malewa Gorge
Prolonged Drift
Olorgesailie
Prospect Farm
Lukenya Hill
Sonjo Buri
Nasera
Naisiusiu/Ndutu
Lolchoro
Eyasi Shore/Mumba
Panga ya Saidi
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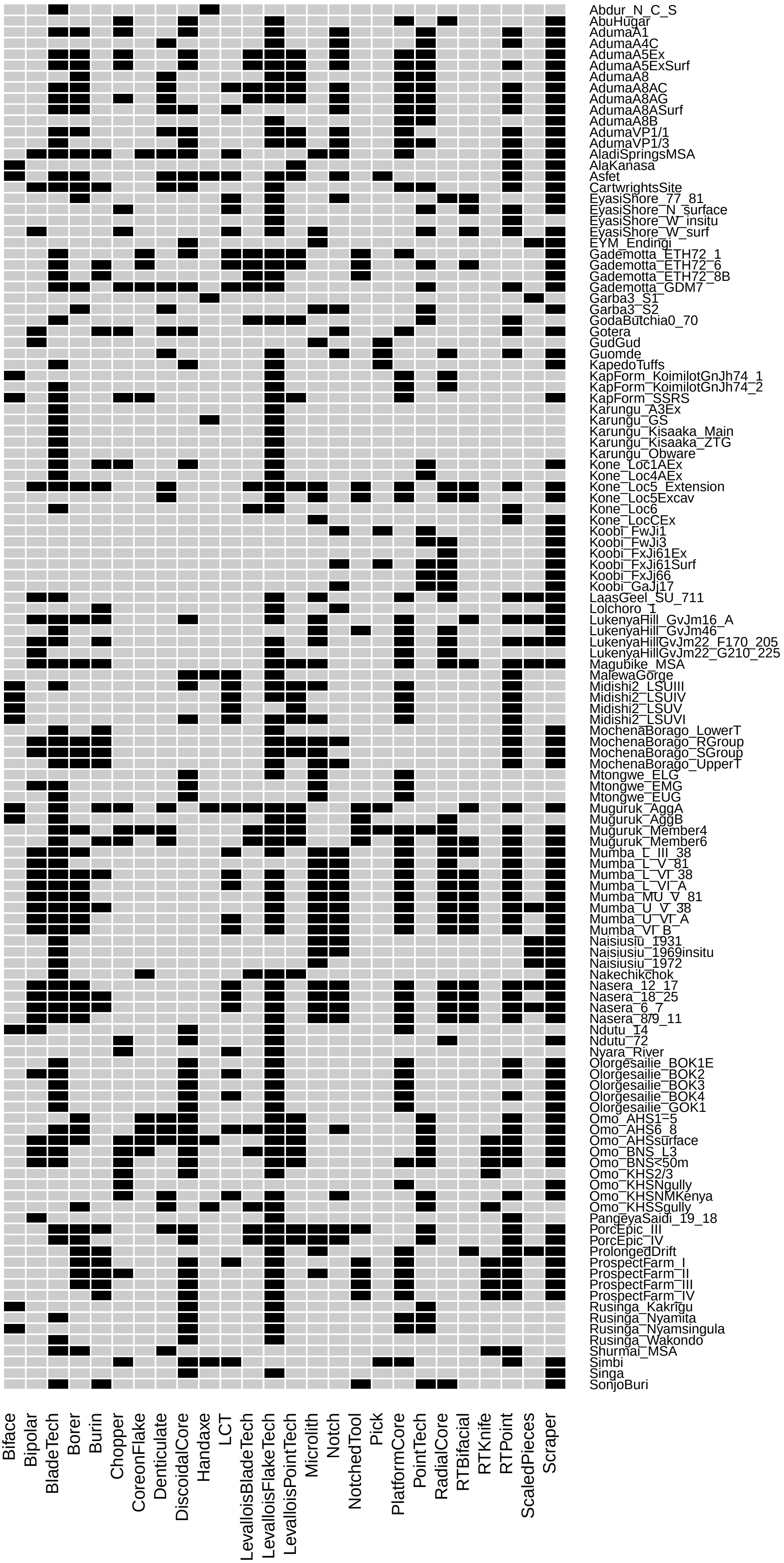

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AlaKanasa
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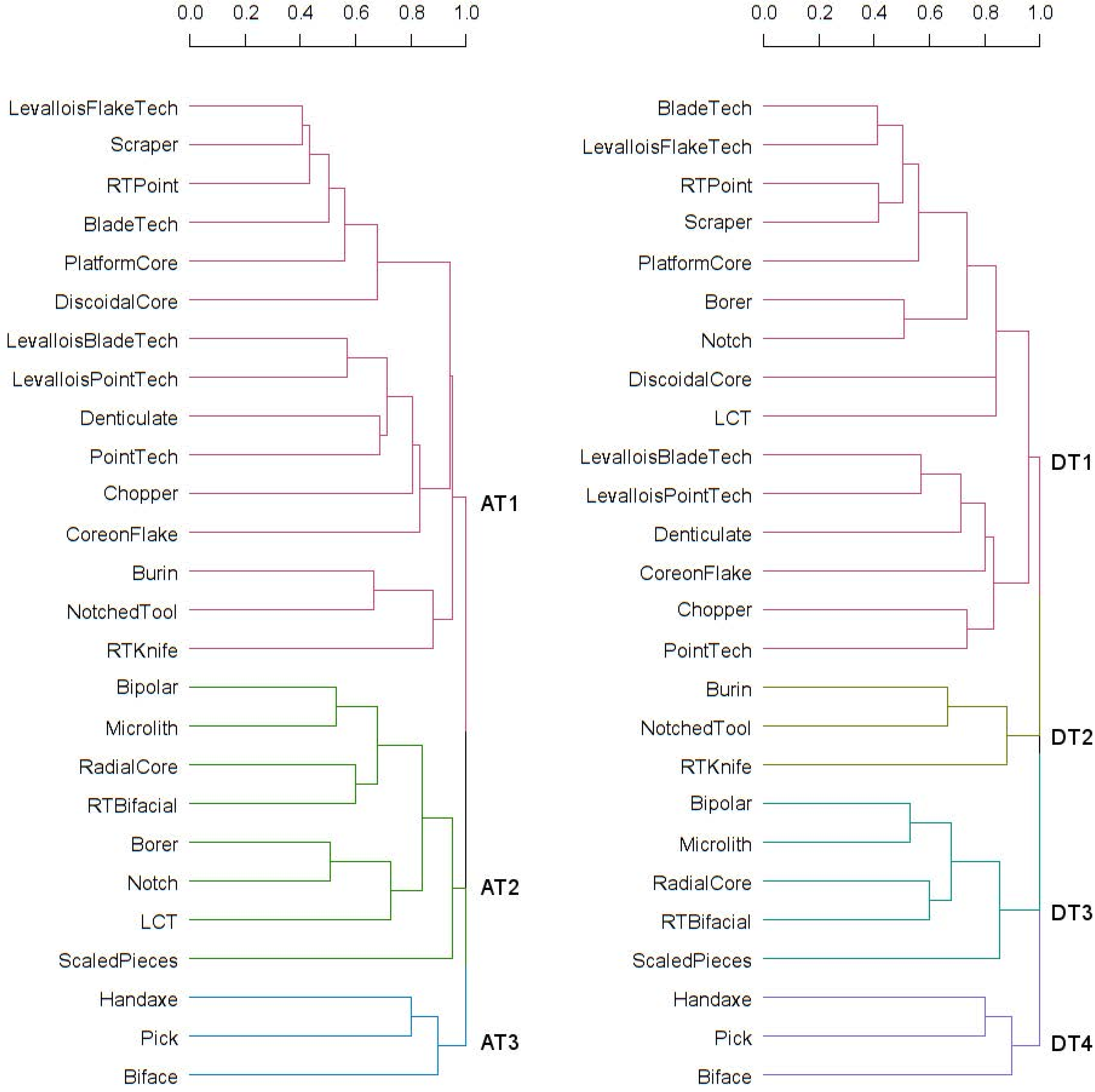

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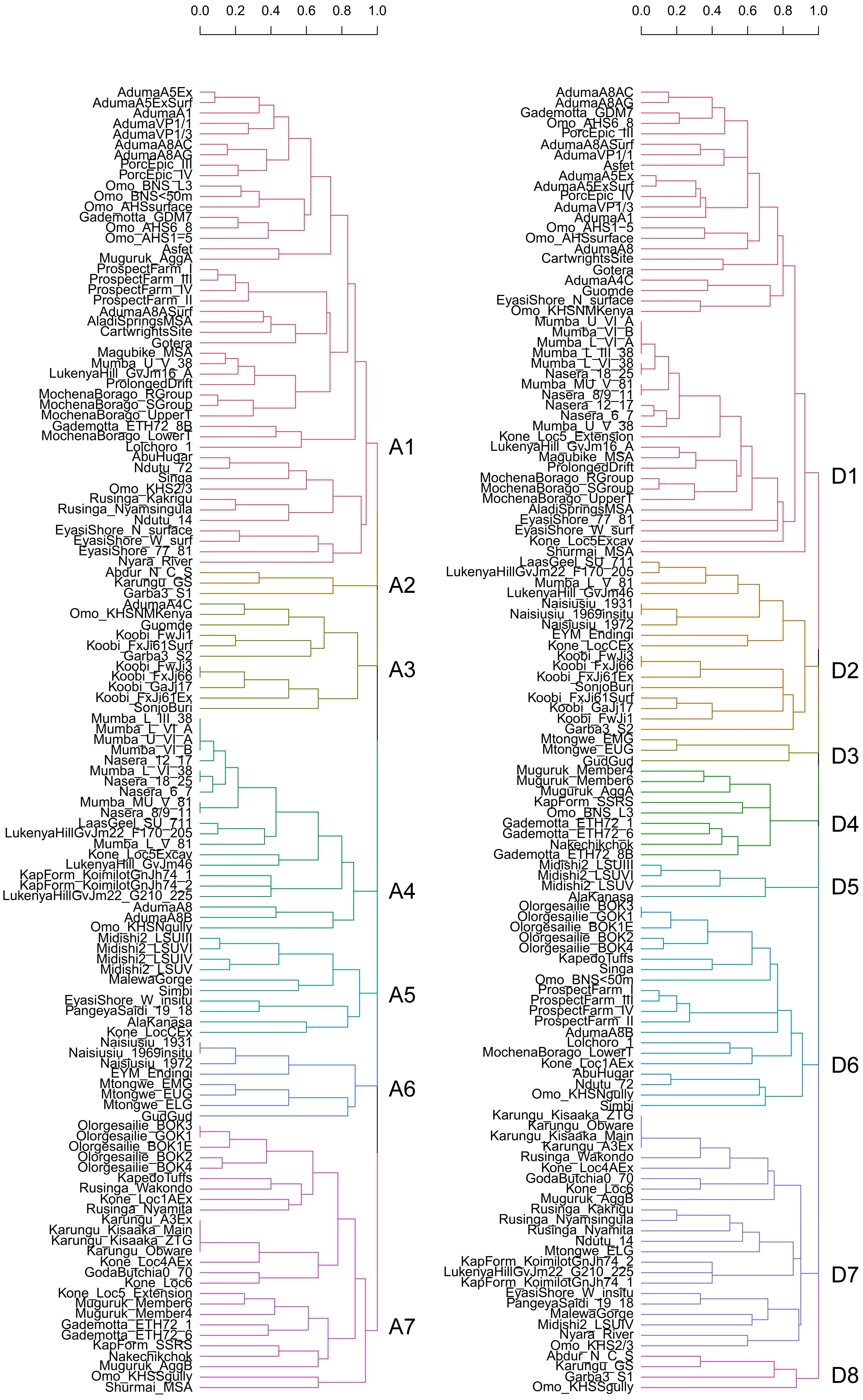
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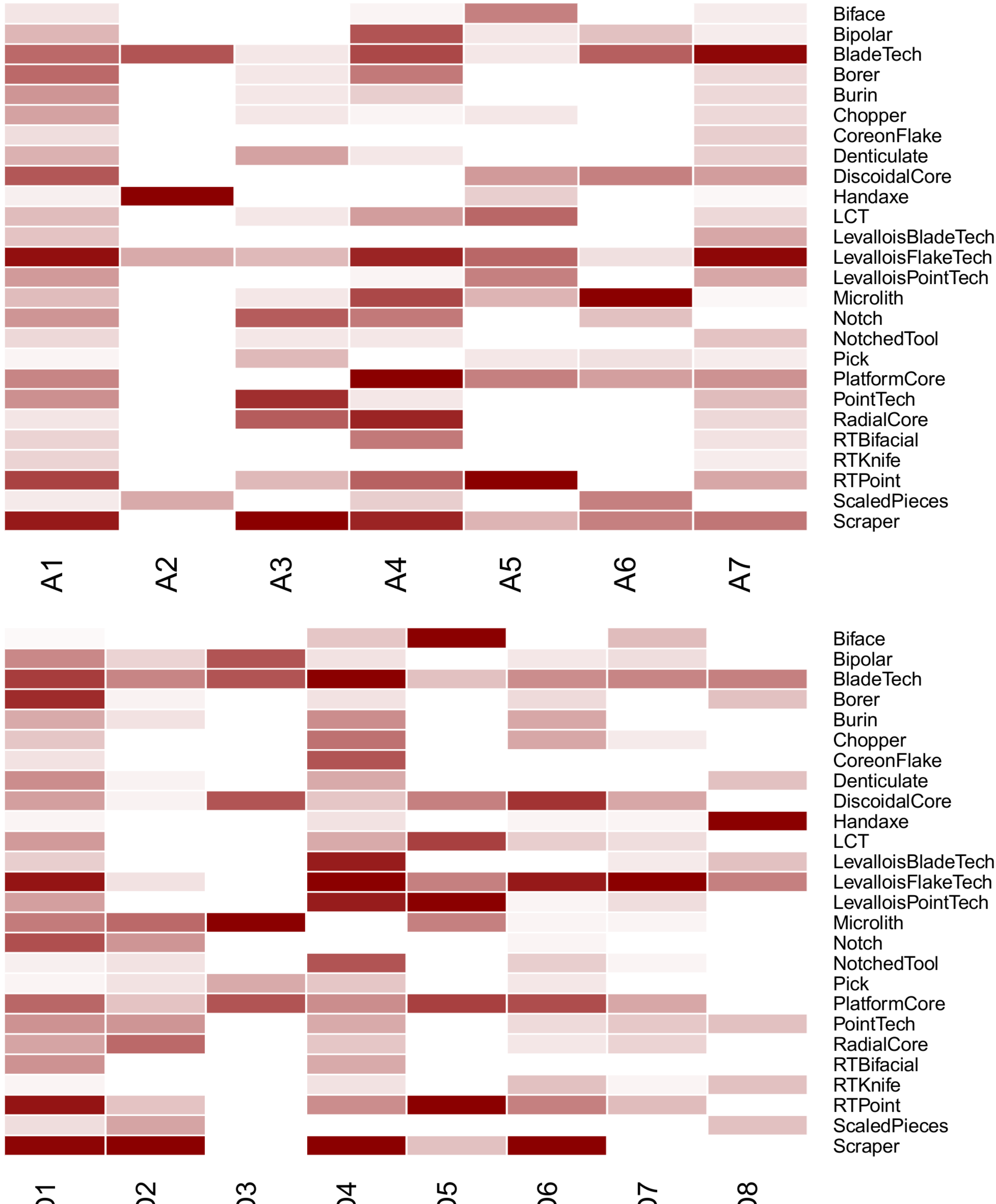
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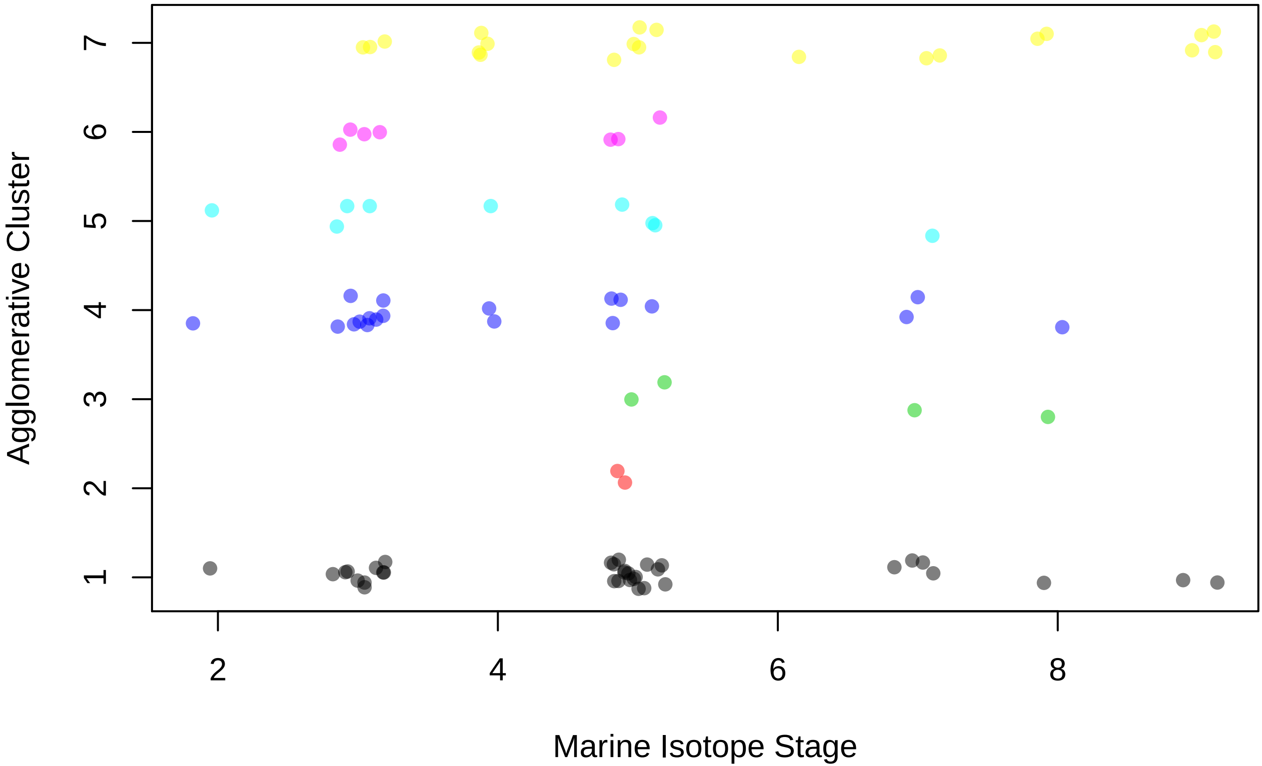

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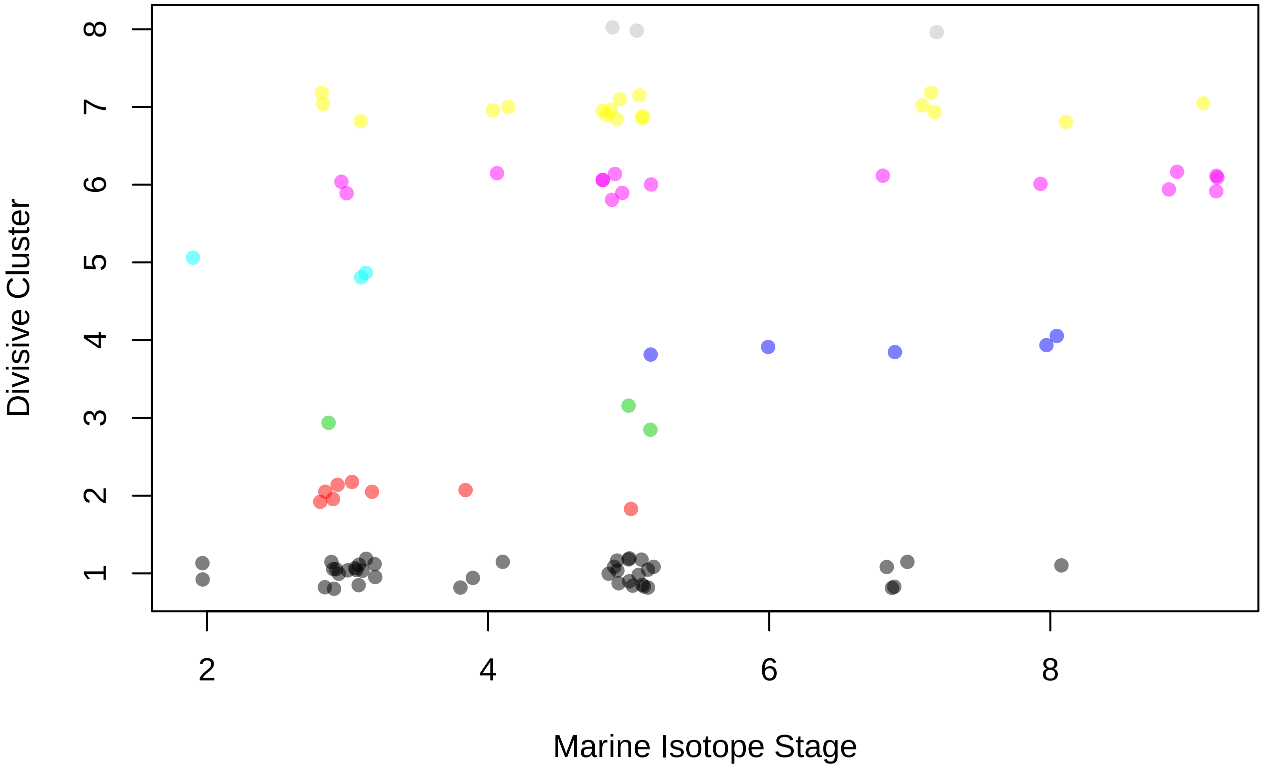

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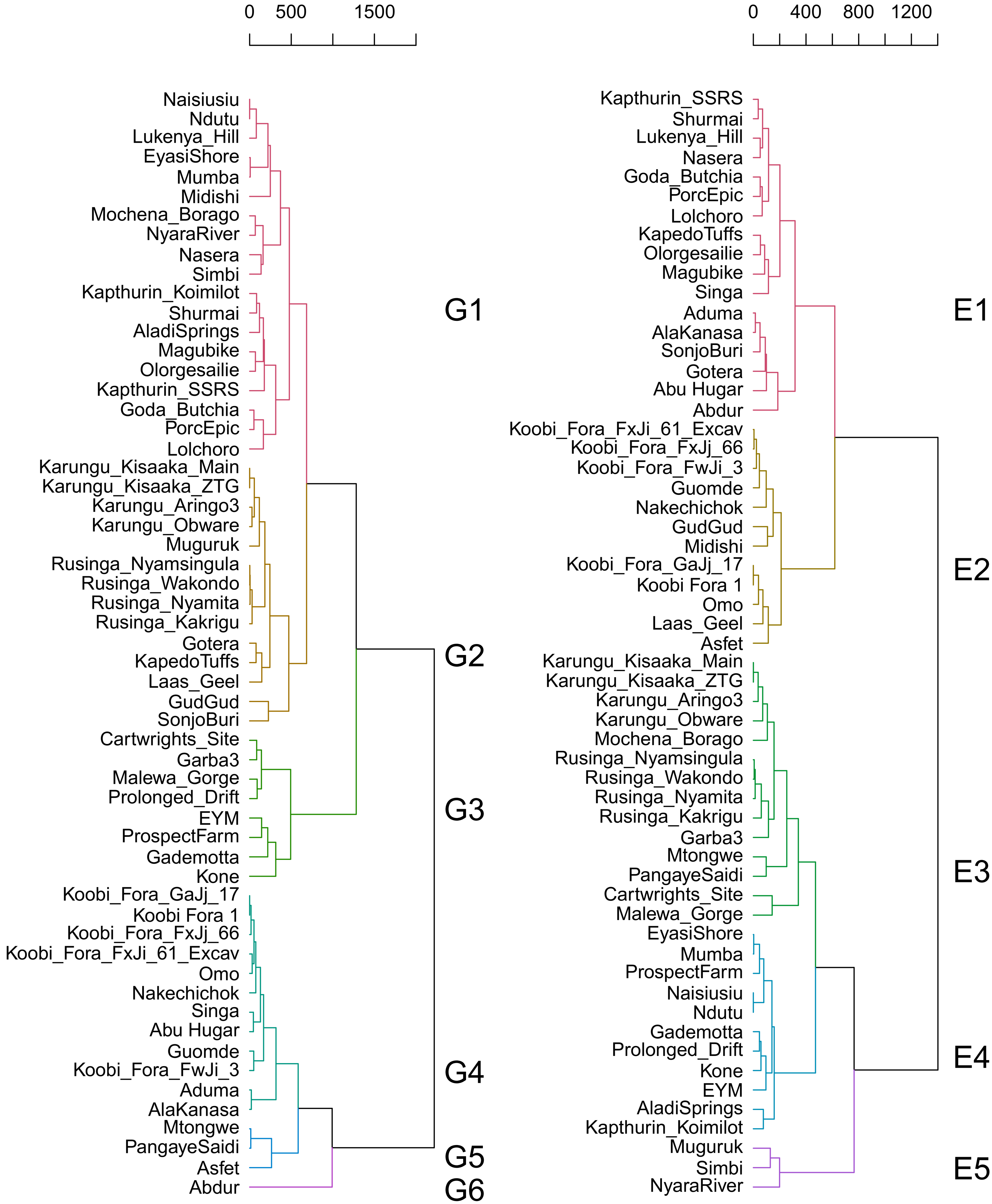

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Simbi
Kapthurin_Koimilot
Shurmai
AladiSprings
Magubike
Olorgesailie
Kapthurin_SSRS
Goda_Butchia
PorcEpic
Lolchoro
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Karungu_Kisaaka_ZTG
Karungu_Aringo3
Karungu_Obware
Muguruk
Rusinga_Nyamsingula
Rusinga_Wakondo
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Singa
Aduma
AlaKanasa
SonjoBuri
Gotera
Abu Hugar
Abdur
Koobi_Fora_FxJi_61_Excav
Koobi_Fora_FxJj_66
Koobi_Fora_FwJi_3
Guomde
Nakechichok
GudGud
Midishi
Koobi_Fora_GaJj_17
Koobi Fora 1
Omo
Laas_Geel
Asfet
Karungu_Kisaaka_Main
Karungu_Kisaaka_ZTG
Karungu_Aringo3
Karungu_Obware
Mochena_Borago
Rusinga_Nyamsingula
Rusinga_Wakondo
Rusinga_Nyamita
Rusinga_Kakrigu
Garba3
Mtongwe
PangayeSaidi
Cartwrights_Site
Malewa_Gorge
EyasiShore
Mumba
ProspectFarm
Naisiusiu
Ndutu
Gademotta
Prolonged_Drift
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Simbi
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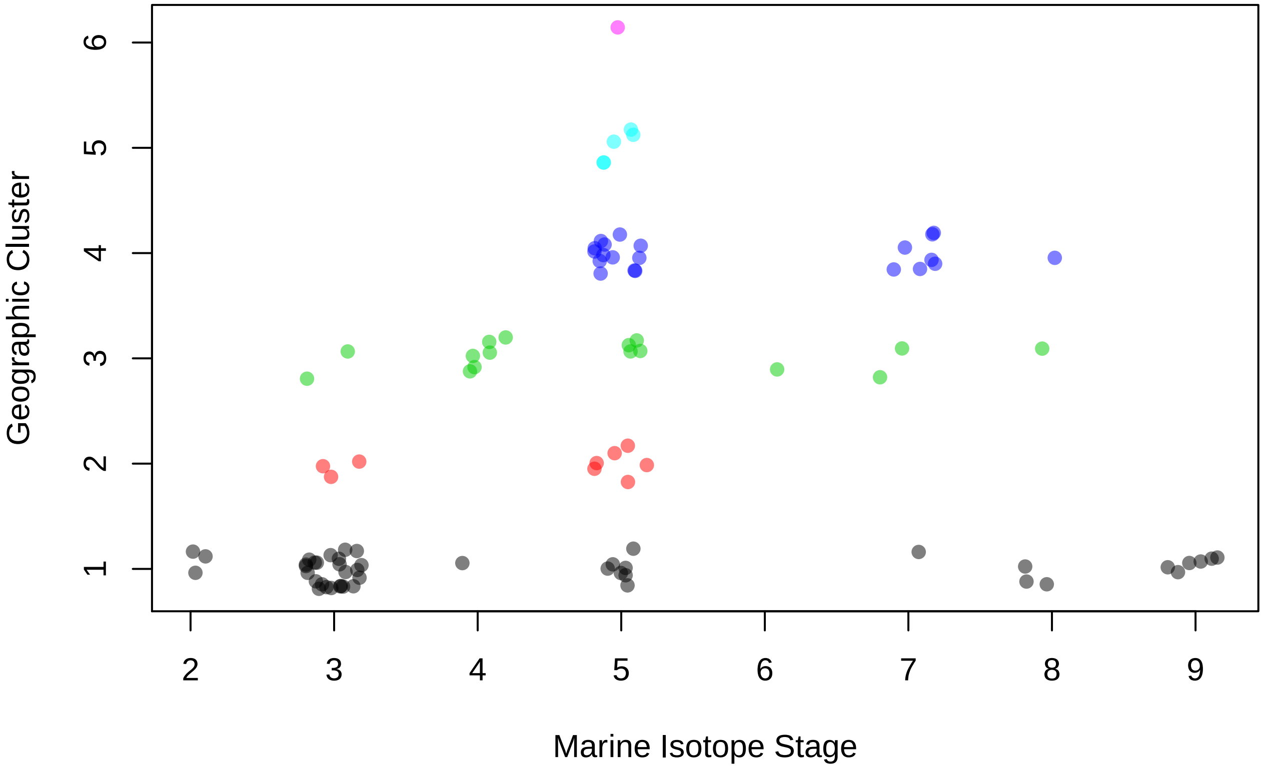
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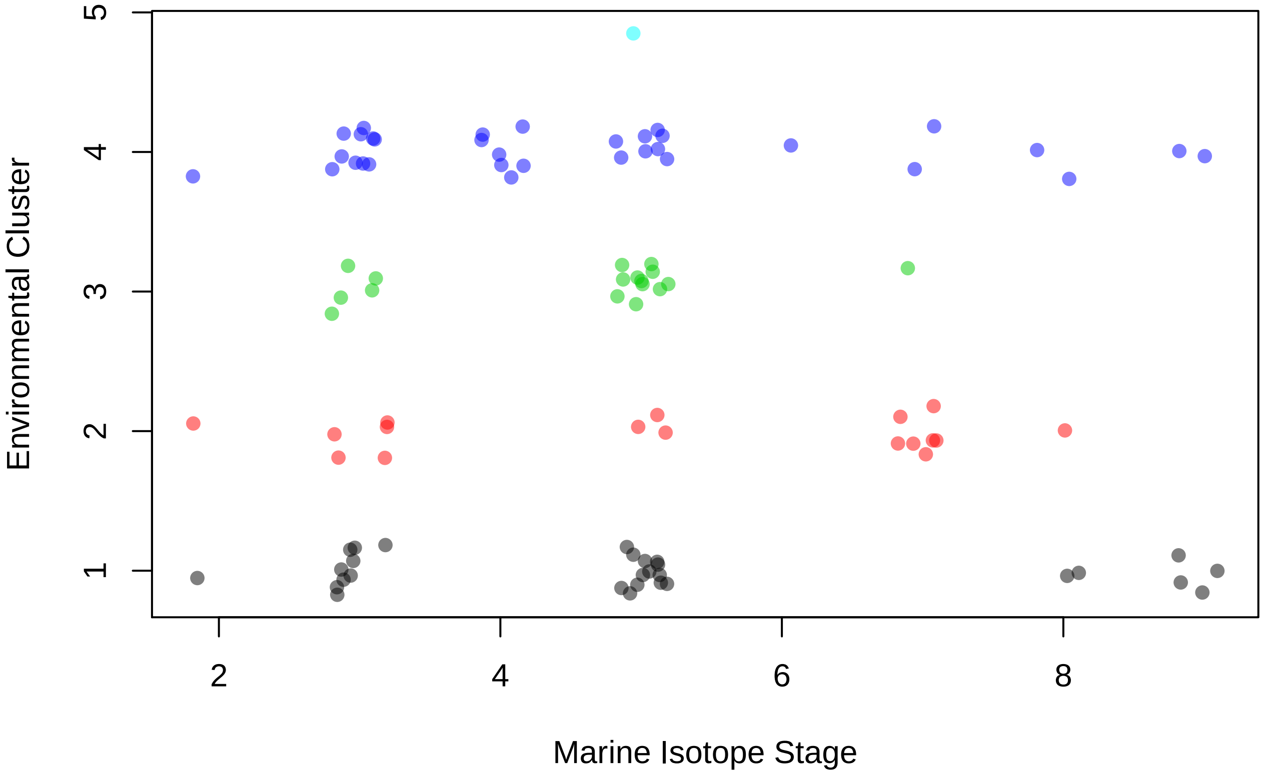

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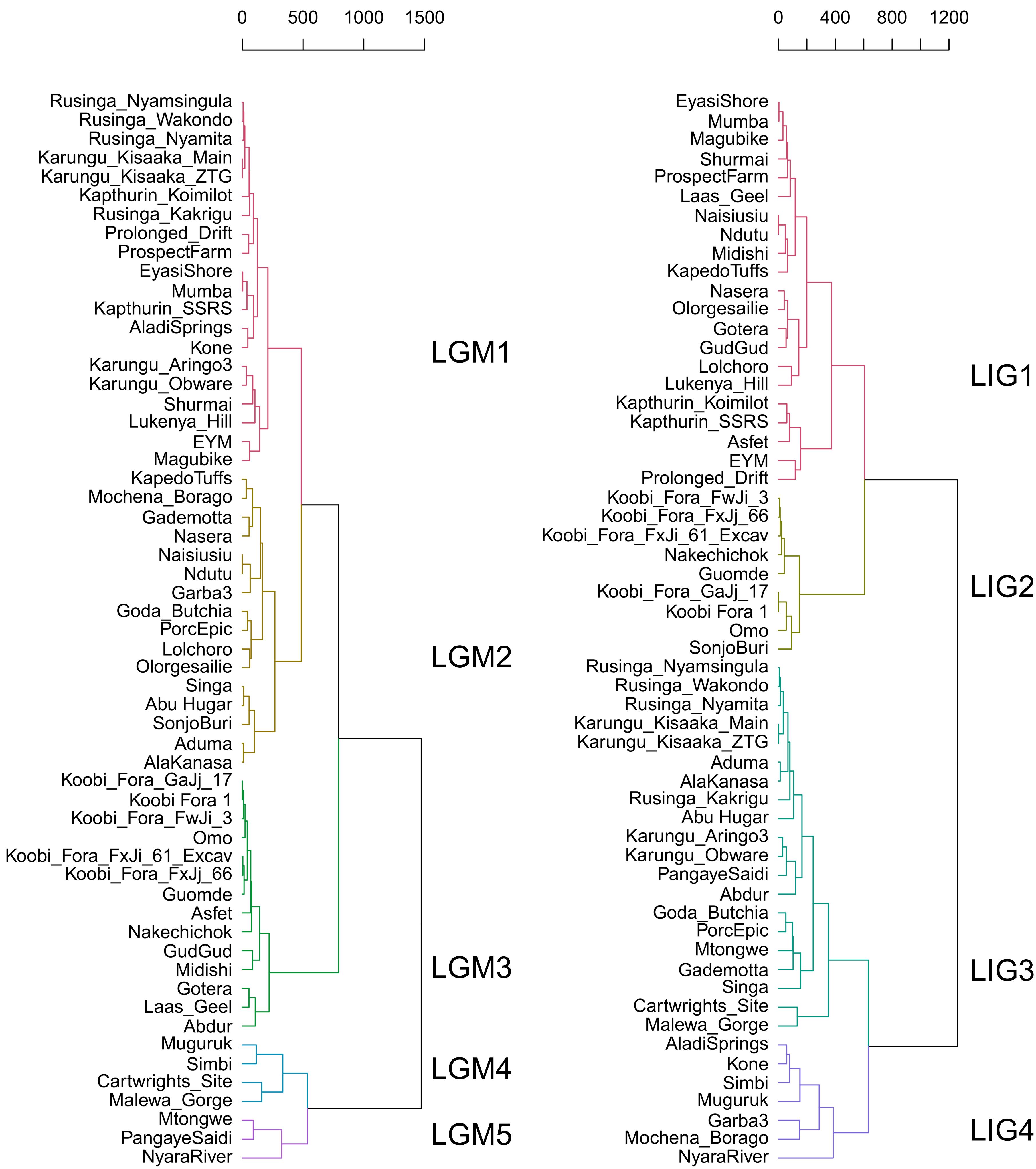
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Guomde
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Mumba
Magubike
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ProspectFarm
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Midishi
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Gotera
GudGud
Lolchoro
Lukenya_Hill
Kapthurin_Koimilot
Kapthurin_SSRS
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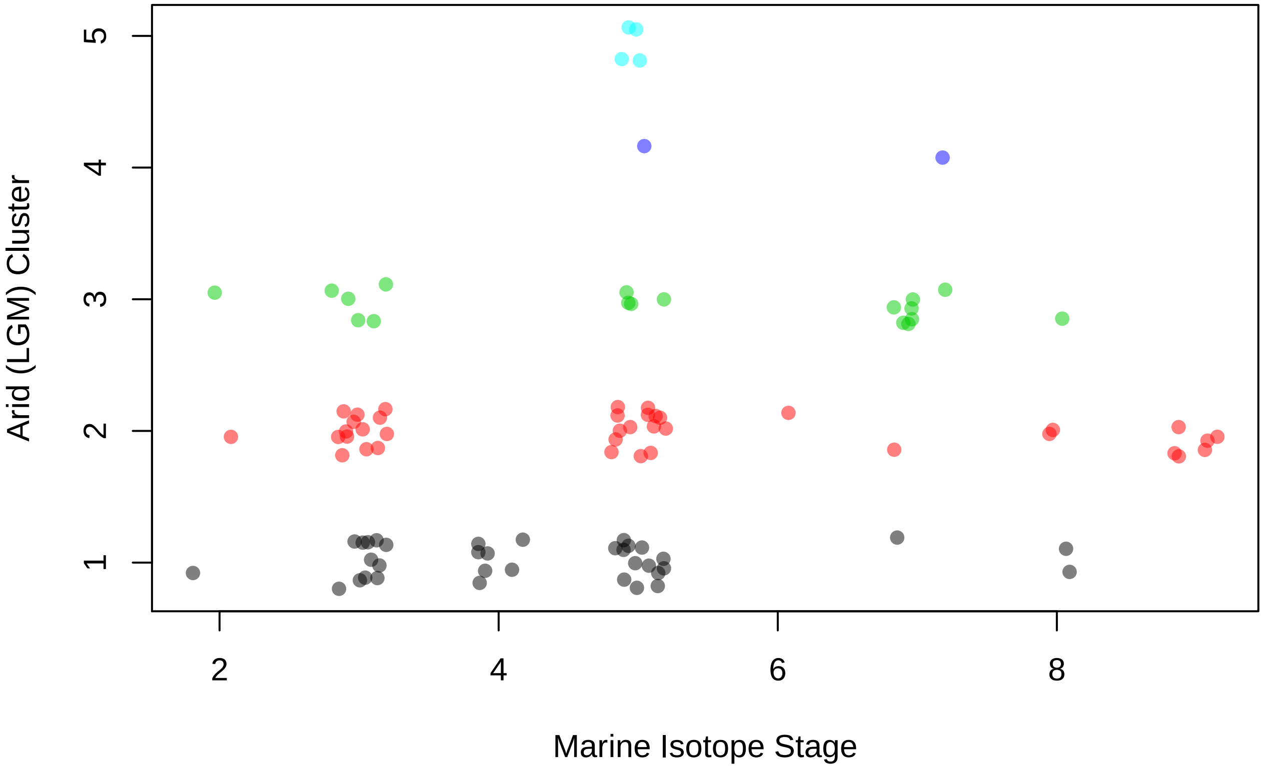

Arid (LGM) Cluster
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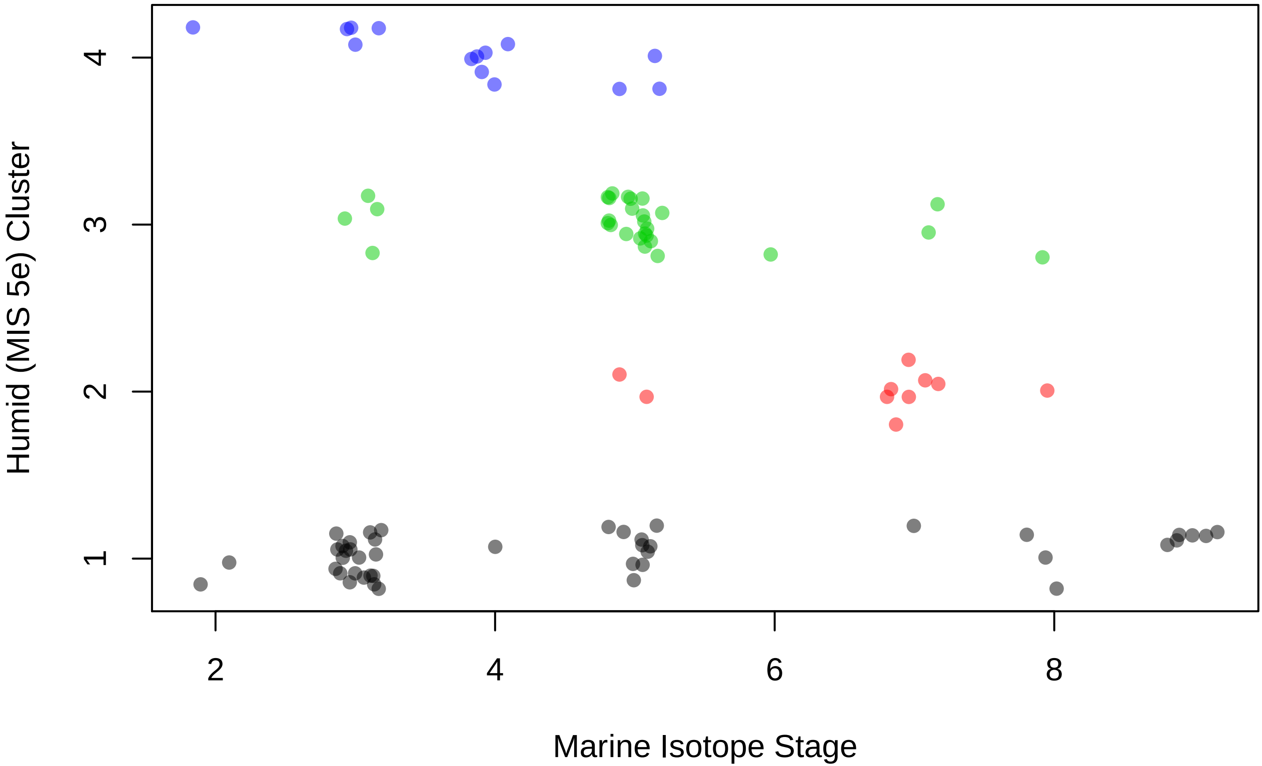
Marine Isotope Stage



Humid (MIS 5e) Cluster
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Marine Isotope Stage

The structure of the Middle Stone Age of eastern Africa: Supplementary Information

Table SI.1: Assemblages used in analysis, identifying site/area name, assemblage name, latitude, longitude Marine Isotope Stage and references.

Site	Assemblage	N	E	MIS	Ref
Abdur	AN, AC and AS	15.13	39.68	5	Bruggemann 2004; Walter et al. 2000
Abu Hugar	Abu Hugar	12.86	33.99	NA	Clark 1988
Aduma	A1	10.393	40.537	5	Yellen 2005
Aduma	A4 Contact	10.393	40.537	5	Yellen 2005
Aduma	A5 Excavated	10.393	40.537	5	Yellen 2005
Aduma	A5 (excavated surface)	10.393	40.537	5	Yellen 2005
Aduma	A8	10.393	40.537	5	Yellen 2005
Aduma	A8A Contact	10.393	40.537	5	Yellen 2005
Aduma	A8A Gravel	10.393	40.537	5	Yellen 2005
Aduma	A8A surface	10.393	40.537	5	Yellen 2005
Aduma	A8B	10.393	40.537	5	Yellen 2005
Aduma	VP 1/1	10.393	40.537	5	Yellen 2005
Aduma	VP 1/3	10.393	40.537	5	Yellen 2005
Aladi Springs	Aladi Springs	9.25	40.75	2	Gossa et al. 2012
Ala Kanasa	Ala Kanasa	10.52	40.53	NA	Clark 1988
Asfet	Asfet	15.29	39.91	5	Beyin 2013
Cartwrights Site	Cartwrights Site	-0.63	36.46	NA	Waweru 2007
Eyasi Shore	77_81	-3.54	35.28	5	Mehlman 1989
Eyasi Shore	Nordostbucht surface	-3.54	35.28	5	Mehlman 1989
Eyasi Shore	Westbucht in situ	-3.54	35.28	5	Mehlman 1989
Eyasi Shore	Westbucht surface	-3.54	35.28	5	Mehlman 1989
Enkapune ya Muto	RBL4	0.00	36.15	NA	Basell 2008
Gademotta	ETH_72_1	7.55	38.57	7	Douze 2012
Gademotta	ETH_72_6	7.55	38.57	6	Douze 2012
Gademotta	ETH_72_8B	7.55	38.57	8	Douze 2012
Gademotta	GDM7	7.55	38.57	NA	Sahle et al. 2013
Garba 3	Sample 1	8.41	38.34	5	Mussi 2013
Garba 3	Sample 2	8.41	38.34	5	Mussi 2013
Goda Butchia	0-70cm	9.541	41.62	3	Pleurdeau et al. 2014
Gotera	Gotera	4.70	37.40	NA	Basell 2008
GudGud	GudGud	10.87	48.26	3	Basell 2008
Guomde	Guomde	3.61	36.52	8	Basell 2008
KapedoTuffs	Combined	1.07	36.08	5	Tryon et al. 2008
Kapthurin Formation	Koimilot GnJh74 Locus 1	0.517	35.975	8	Tryon 2003

Kapthurin Formation	Koimilot GnJh74 Locus 2	0.517	35.975	7	Tryon 2003
Kapthurin Formation	SSRS	0.657	35.99	8	Blegen et al. 2017
Karungu	Aringo 3 Excavation	-0.83	34.18	5	Faith et al. 2015
Karungu	General Survey	-0.80	34.13	NA	Faith et al. 2015
Karungu	Kisaaka-Main	-0.80	34.13	3	Faith et al. 2015
Karungu	Kisaaka-ZTG	-0.80	34.13	5	Faith et al. 2015
Karungu	Obware	-0.87	34.22	NA	Faith et al. 2015
Kone	Loc1_A_TrialEx	8.43	39.66	4	Kurashina 1978
Kone	Loc4_A_TrialEx	8.43	39.66	4	Kurashina 1978
Kone	Loc5_Extension	8.43	39.66	4	Kurashina 1978
Kone	Loc5_1975ex	8.43	39.66	4	Kurashina 1978
Kone	Loc6	8.43	39.66	4	Kurashina 1978
Kone	LocC_testEx	8.43	39.66	4	Kurashina 1978
Koobi_Fora	FwJi 1	4.28	36.25	NA	Kelly 1996
Koobi_Fora	FwJi 3	4.30	36.22	NA	Kelly 1996
Koobi_Fora	FxJi 61 Excav	4.04	36.43	NA	Kelly 1996
Koobi_Fora	FxJi 61 Surf	4.04	36.43	NA	Kelly 1996
Koobi_Fora	FxJj 66	4.05	36.42	NA	Kelly 1996
Koobi_Fora	GaJj 17	3.97	36.29	NA	Kelly 1996
Laas Geel	SU_711	9.68	44.27	3	Gutherez et al. 2014
Lolchoro	1	-2.97	35.96	NA	Seitsonen 2005
LukenyaHill_GvJm16	A	-1.65	37.14	NA	Merrick 1975
LukenyaHill_GvJm46	LukenyaHill_GvJm46	-1.65	37.14	3	Kelly 1996; Basell 2008
Lukenya Hill GvJm22	F - 170 - 205	-1.65	37.14	NA	Tryon et al. 2015
Lukenya Hill GvJm22	G - 210-225	-1.65	37.14	NA	Tryon et al. 2015
Magubike	TP1/2/3	-7.76	35.47	3	Bushozi 2011
Malewa Gorge	Malewa Gorge	-0.77	36.39	7	Basell 2008
Midishi 2	LSU III	10.60	47.73	2	Tryon & Faith 2013
Midishi 2	LSU IV	10.60	47.73	3	Tryon & Faith 2013
Midishi 2	LSU V	10.60	47.73	3	Tryon & Faith 2013
Midishi 2	LSU VI	10.60	47.73	3	Tryon & Faith 2013
Mochena Borago	Lower T	6.90	37.74	3	Brandt et al. 2017
Mochena Borago	R Group	6.90	37.74	3	Brandt et al. 2017
Mochena Borago	S Group	6.90	37.74	3	Brandt et al. 2017
Mochena Borago	Upper T	6.90	37.74	3	Brandt et al. 2017
Mtongwe	East_Lower_Group	-4.08	39.65	5	Tryon & Faith 2013
Mtongwe	East_Middle_Group	-4.08	39.65	5	Tryon & Faith 2013
Mtongwe	East Upper Group	-4.08	39.65	5	Tryon & Faith 2013
Muguruk	Agg A	-0.09	34.63	NA	McBrearty 1988
Muguruk	Agg B	-0.09	34.63	NA	McBrearty 1988

Muguruk	Member 4	-0.09	34.63	NA	McBrearty 1986
Muguruk	Member 6	-0.09	34.63	NA	McBrearty 1986
Mumba	Lower III 1938 G_H	-3.54	35.29	3	Mehlman 1989
Mumba	Lower_V_77_81	-3.54	35.29	3	Mehlman 1989
Mumba	Lower V_1938_G	-3.54	35.29	3	Mehlman 1989
Mumba	Lower VI_A	-3.54	35.29	5	Mehlman 1989
Mumba	Middle Upper V 77_81	-3.54	35.29	3	Mehlman 1989
Mumba	Upper V 1938 B	-3.54	35.29	3	Mehlman 1989
Mumba	Upper VI_A	-3.54	35.29	4	Mehlman 1989
Mumba	VI_B	-3.54	35.29	5	Mehlman 1989
Naisiusiu	1931 material	-3.25	34.86	3	Leakey et al. 1972
Naisiusiu	1969 in situ material	-3.25	34.86	3	Leakey et al. 1972
Naisiusiu	1972_surface	-3.25	34.86	3	Leakey et al. 1972
Nakechikchok	Nakechikchok	3.15	35.8	NA	Shea et al. 2010
Nasera	12_17	-2.73	35.35	3	Mehlman1989
Nasera	18_25	-2.73	35.35	3	Mehlman1989
Nasera	6_7	-2.73	35.35	2	Mehlman1989
Nasera	8/9_11	-2.73	35.35	3	Mehlman1989
Ndutu	Ndutu	-3.25	34.86	9	Eren et al. 2014
Ndutu	Ndutu	-3.25	34.86	9	Leakey et al. 1972
Nyara_River	Nyara_River	-8.97	33.46	NA	Basell 2008
Olorgesailie	BOK1E	-1.56	36.43	9	Brooks et al. 2018
Olorgesailie	BOK2	-1.56	36.43	9	Brooks et al. 2018
Olorgesailie	BOK3	-1.56	36.43	9	Brooks et al. 2018
Olorgesailie	BOK4	-1.56	36.43	9	Brooks et al. 2018
Olorgesailie	GOK1	-1.56	36.43	8	Brooks et al. 2018
Omo	AHS 1-5	4.46	35.97	7	Shea et al. 2008
Omo	AHS 6_8	4.46	35.97	7	Shea et al. 2008
Omo	AHS surface	4.46	35.97	7	Shea et al. 2008
Omo	BNS_L3	4.46	35.97	5	Shea et al. 2008
Omo	BNS<50m	4.46	35.97	5	Shea et al. 2008
Omo	KHS 2/3	4.46	35.97	7	Shea et al. 2008
Omo	KHS N gully	4.46	35.97	7	Shea et al. 2008
Omo	KHS NM Kenya	4.46	35.97	7	Shea et al. 2008
Omo	KHS S gully	4.46	35.97	7	Shea et al. 2008
Pange ya Saidi	19_18	-3.72	39.71	5	Shipton et al 2018
Porc Epic	III	9.56	41.88	3	Pleurdeau 2003
Porc Epic	IV	9.56	41.88	3	Pleurdeau 2003
ProlongedDrift	ProlongedDrift	-0.76	35.94	3	Waweru 2007
ProspectFarm	I	-0.93	36.11	NA	Anthony 1978

ProspectFarm	II	-0.93	36.11	5	Anthony 1978
ProspectFarm	III	-0.93	36.11	5	Anthony 1978
ProspectFarm	IV	-0.93	36.11	3	Anthony 1978
Rusinga	Kakrigu	-0.45	34.05	NA	Tryon & Faith 2013
Rusinga	Nyamita	-0.42	34.15	5	Tryon & Faith 2013
Rusinga	Nyamsingula	-0.40	34.18	5	Tryon & Faith 2013
Rusinga	Wakondo	-0.41	34.17	5	Tryon & Faith 2013
Shurmai	MSA	0.50	37.21	3	Dickson & Gang
Simbi	Simbi	-0.54	35.04	5	Basell 2008
Singa	Singa	11.99	34.20	NA	Basell 2008
SonjoBuri	SonjoBuri	-2.34	36.04	NA	Seitsonen 2005

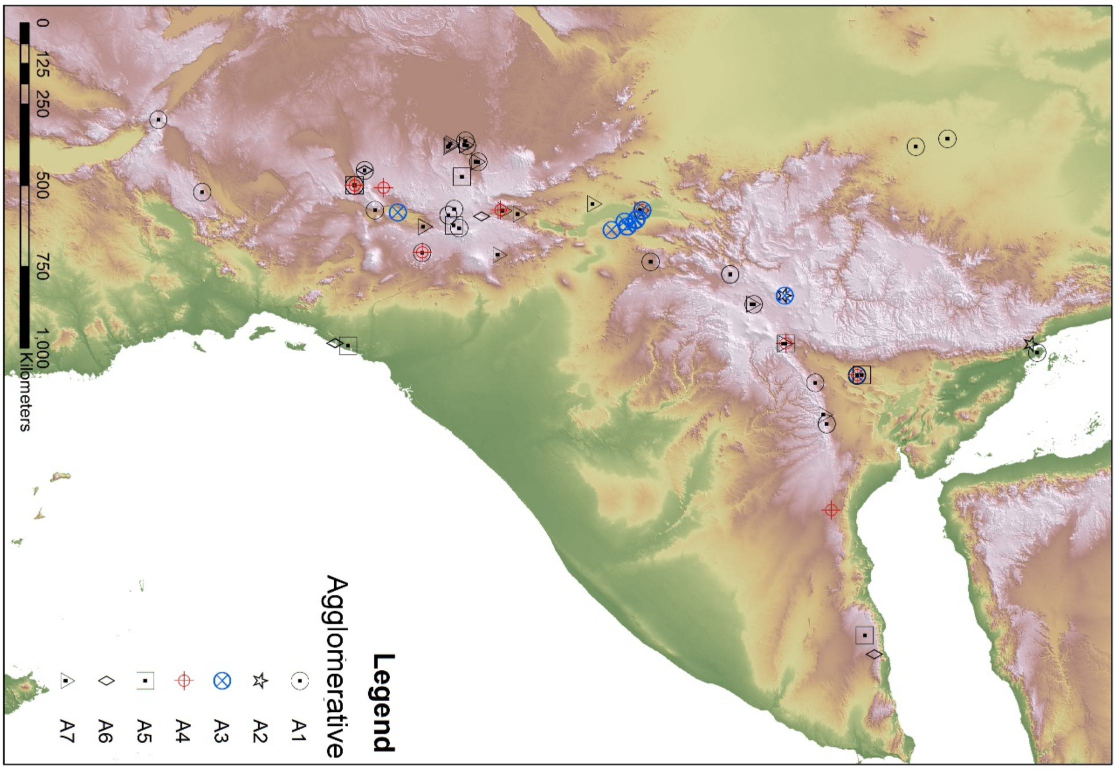
Table SI.2: Description of assemblage composition of clusters identified using an agglomerative approach.

A1 (n=46)	This cluster is unique in including at least one occurrence of every stone tool type, but no single type is ubiquitous. The most numerous types are *Levallois Flake Technology* (93.5%), *Scrapers* (89.1%), *RT Points* (73.9%), with *Discoidal Cores* (65.2%), *Blade Technology* and *Borers* (both 58.7%) occurring in more than half of the assemblages.
A2 (n=3)	All three members of this cluster include *Handaxes*, with 2/3 including *Blade Technology*, and 1/3 including *Levallois Flake Technology* and *Scaled Pieces*, but no other tool types are present.
A3 (n=11)	All members of this cluster include scrapers, with *Point Technology* (81.8%), and *Notches* and *Radial Cores* (both 63.6%) appear in more than half of the assemblages, with a total of 15 artefact types represented.
A4 (n=21)	All members of this cluster include *Platform Cores*, with 10 other types appearing in more than half of the assemblages, including *Scrapers*, *Radial Cores* and *Levallois Flake Technology* (all 85.7%), and *Blade Technology* and *Microliths* (both 71.4%) appearing in high frequency. Only 6 types are entirely absent.
A5 (n=10)	*RT Points* are found in all members of this cluster, with *Levallois Flake Technology* and *LCT*'s occurring in 6/10 sites, and *Platform Cores*, *Levallois Point Technology* and *Bifaces* appearing in 5/10 sites, and 8 other types appear at lower frequencies.
A6 (n=8)	All members of this cluster include *Microliths*, with *Blade Technology* present in 5/8 of the sites, and *Discoidal Cores*, *Scrapers* and *Scaled Pieces* appear in half the assemblages. 16 tool types are absent from this cluster.
A7 (n=26)	Two types, *Levallois Flake Technology* and *Blade Technology* occur in 96.2% of assemblages, though no types are entirely ubiquitous. In addition to this, only scrapers appear in more than half of the assemblages, though only two tool types are completely absent

Table SI.2: Description of assemblage composition of clusters identified using an divisive approach.

D1 (n=45)	No types appear in all members of this assemblage, although *Scrapers* (97.8%), *Levallois Flake Technology* and *RT Points* (both 91.1%) occur in high frequency, followed by *Borers* (82.2%), *Blade Technology* (75.6%), and *Notches* (68.9%), with at least one occurrence of all stone tool types present.
D2 (n=17)	*Scrapers* are ubiquitous in this cluster, although beyond this only *Microliths* and *Radial Cores* (both 58.8%) appear in more than half the assemblages, whereas 9 tool types are entirely absent.
D3 (n=3)	All members of this cluster include *Microliths*, with 2/3 including *Blade Technology, Platform Cores, Bipolar Tech* and *Discoidal Cores*, and a single *Pick* occurs.
D4 (n=9)	*Blade Technology, Scrapers* and *Levallois Flake Technology* are ubiquitous in this group, with high proportions of both *Levallois Blade* and *Levallois Point Technologies* (88.9%).
D5 (n=4)	All four members of this cluster include *Bifaces*, *Levallois Point Technology* and *RT Points*, with ¾ including *LCT*'s and *Platform Cores*, out of a total of 10 artefacts present.
D6 (n=20)	*Scrapers* are ubiquitous in this cluster, with *Levallois Flake Technology* (90%), *Discoidal Cores* (80%) and *Platform Cores* (70%) present in more than half of the assemblages, with only 6 artefact types entirely absent.
D7 (n=23)	All members of this cluster contain *Levallois Flake Technology* but none of the remaining 16 artefact types present appear in more than half of the assemblages.
D8 (n=4)	All four members of this cluster includes handaxes, with 2/4 including *Blade Technology* and *Levallois Flake Technology*, with single occurrences of *Levallois Flake Technology*, *Borers*, *Denticulates*, *Levallois Blade Technology*, *Point Technology*, *RT Knife*, and *Scaled Pieces*.

Figure SI.1: Distribution maps of sites grouped by hierarchical clustering using either agglomerative (left) or divisive (right) methods, suggesting most cluster types are widely (although at times sparsely) distributed, with limited spatial structuring.



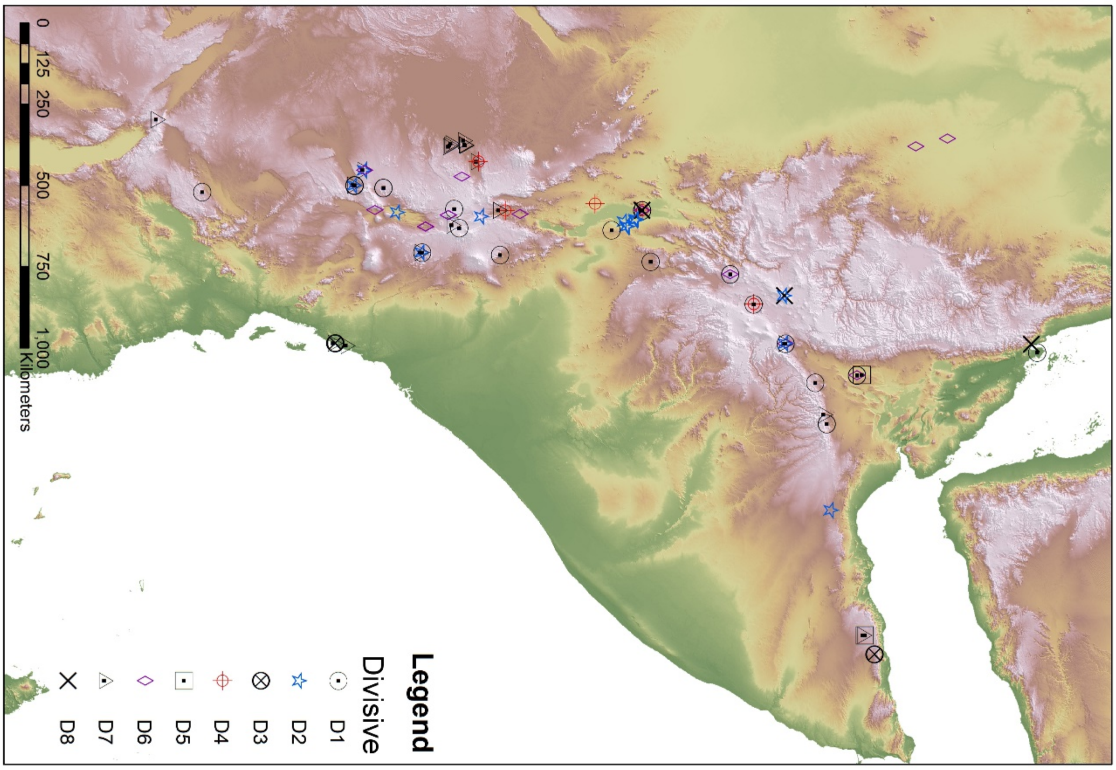


Figure SI.2: (left) Distribution of Geographic Clusters; (top right) jitter plot of assemblage clusters (agglomerative) by geographic clusters; (bottom right) jitter plot of assemblage clusters (divisive) by geographic clusters.

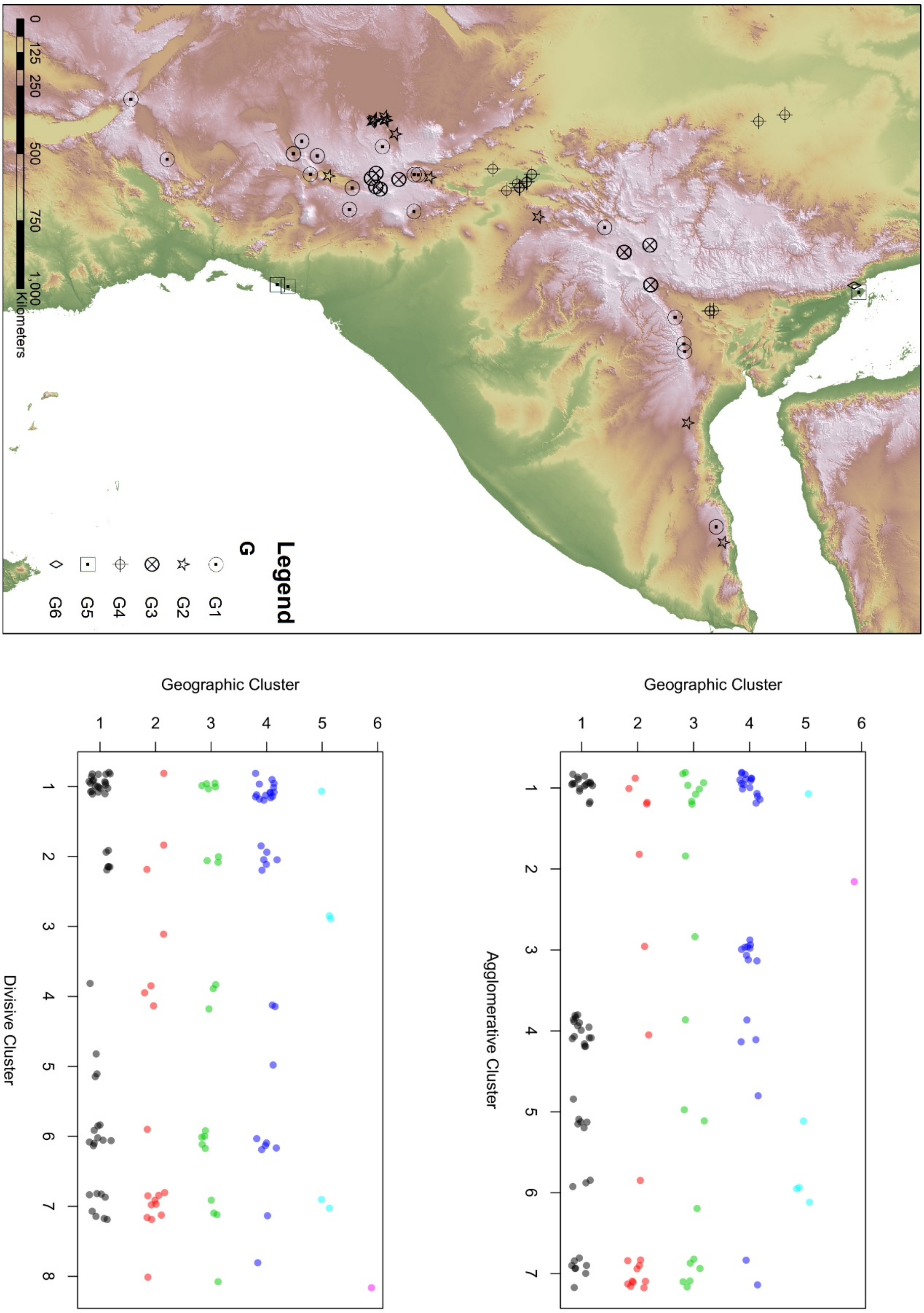


Figure SI.3: (left) Distribution of Modern Environment Clusters; (top right) jitter plot of assemblage clusters (agglomerative) by modern environment clusters; (bottom right) jitter plot of assemblage clusters (divisive) by modern environment clusters.

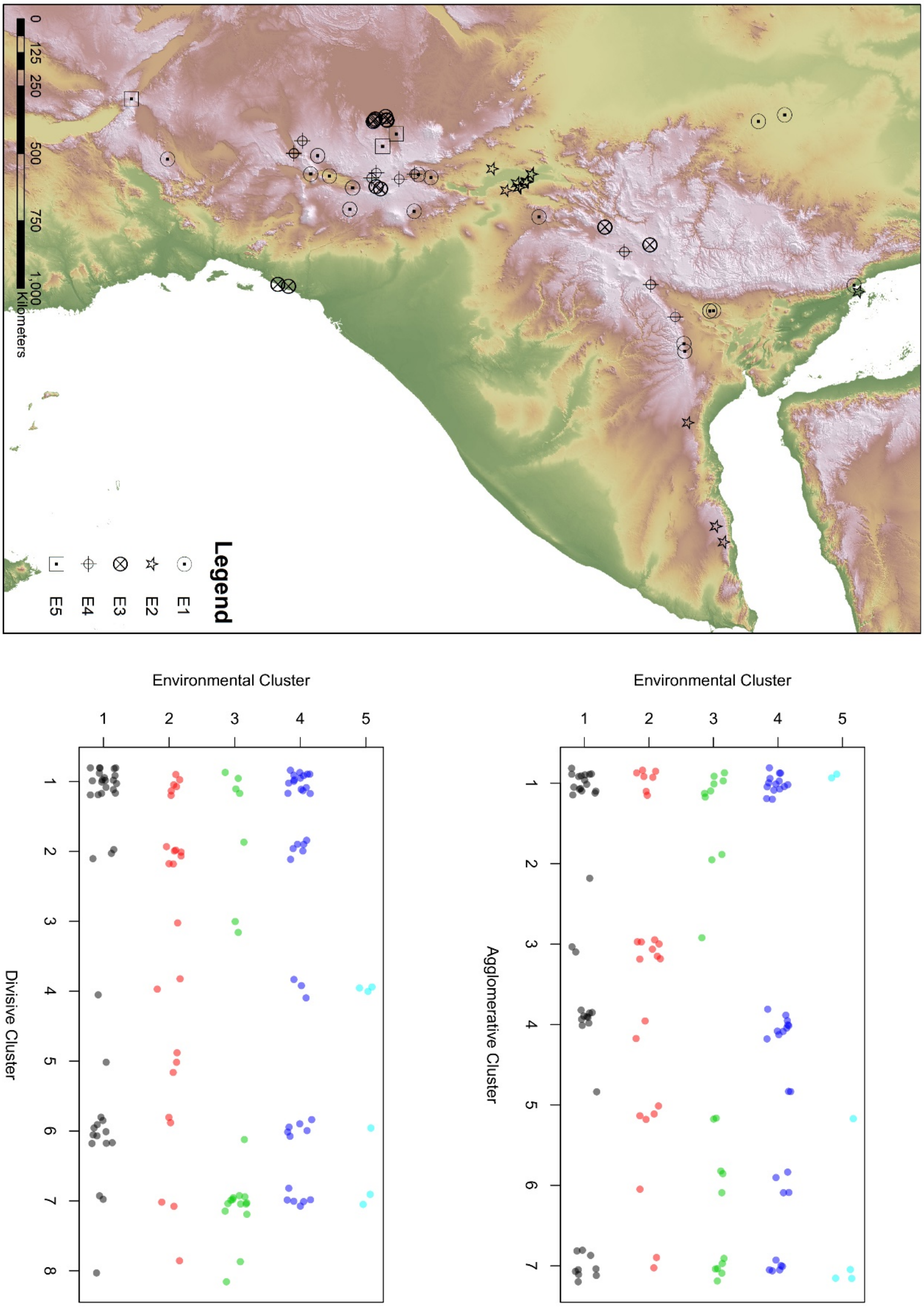


Figure SI.4: Distribution of Arid Environmental Clusters; (top right) jitter plot of assemblage clusters (agglomerative) by arid environmental clusters; (bottom right) jitter plot of assemblage clusters (divisive) by arid environmental clusters.

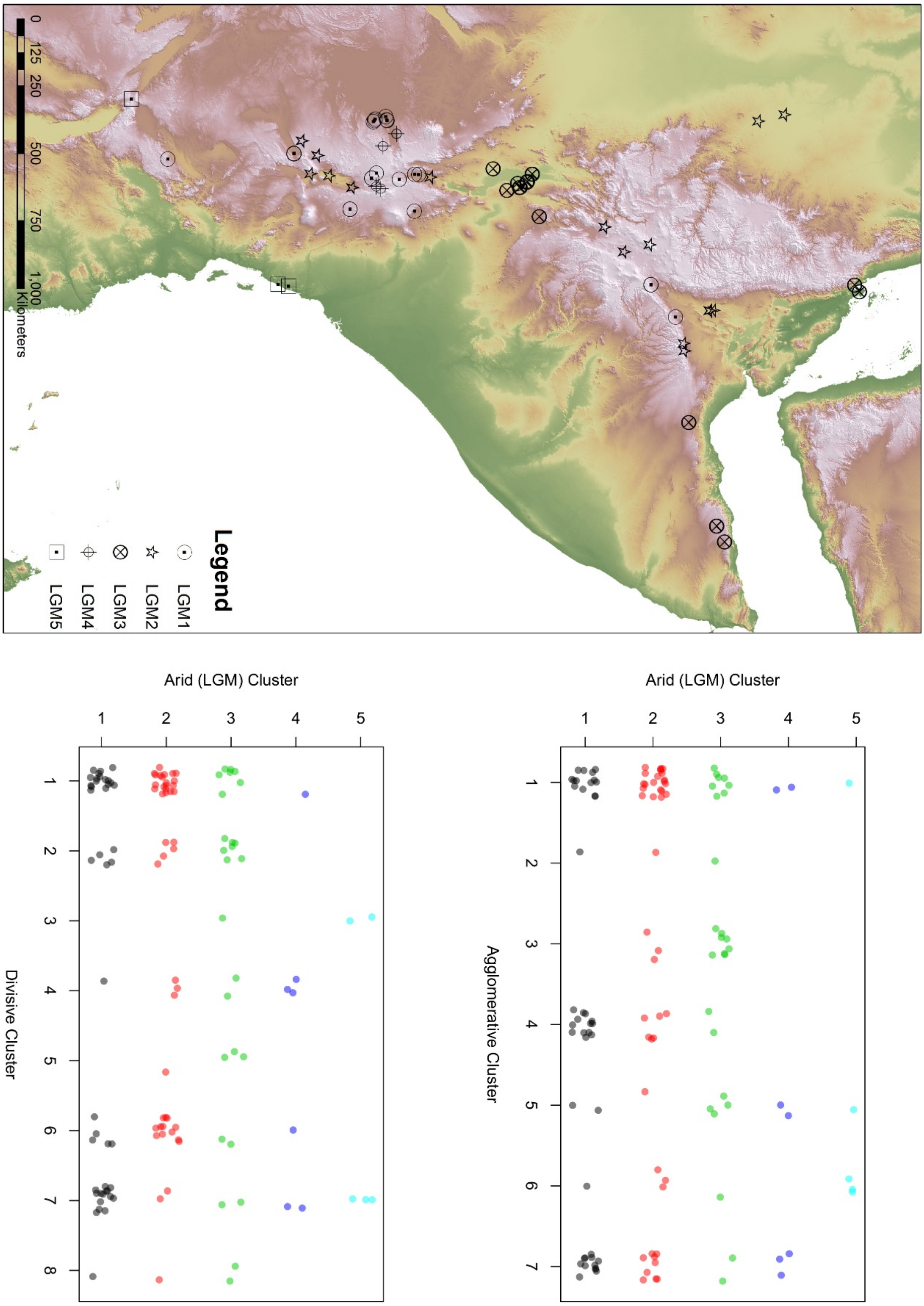
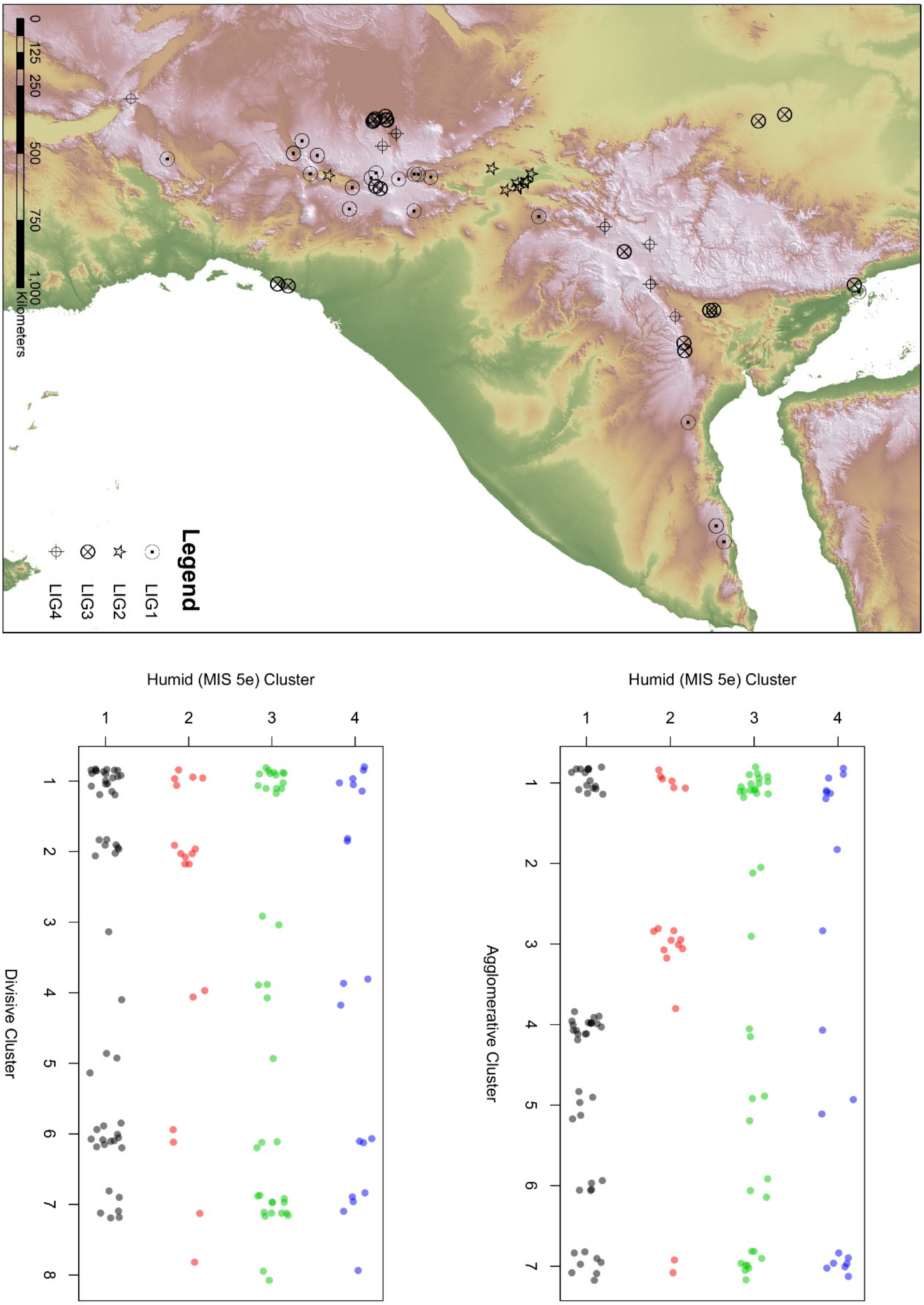


Figure SI.5: Distribution of Humid Environmental Clusters; (top right) jitter plot of assemblage clusters (agglomerative) by humid environmental clusters; (bottom right) jitter plot of assemblage clusters (divisive) by humid environmental clusters.



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