The Middle to Later Stone Age transition at Panga ya Saidi, in the tropical coastal forest of eastern Africa

Abstract

The Middle to Later Stone Age transition is a critical period of human behavioral change that has been variously argued to pertain to the emergence of modern cognition, substantial population growth, and major dispersals of *Homo sapiens* within and beyond Africa. However, there is little consensus about when the transition occurred, the geographic patterning of its emergence, or even how it is manifested in stone tool technology that is used to define it. Here we examine a long sequence of lithic technological change at the cave site of Panga ya Saidi, Kenya, that spans the Middle and Later Stone Age and includes human occupations in each of the last five Marine Isotope Stages. In addition to the stone artifact technology, Panga ya Saidi preserves osseous and shell artifacts enabling broader considerations of the covariation between different spheres of material culture. Several environmental proxies contextualize the artifactual record of human behavior at Panga ya Saidi. We compare technological change between the Middle and Later Stone Age to on-site paleoenvironmental manifestations of wider climatic fluctuations in the Late Pleistocene. The principal distinguishing feature of Middle from Later Stone Age technology at Panga ya Saidi is the preference for fine-grained stone, coupled with the creation of small flakes (miniaturization). Our review of the Middle to Later Stone Age transition elsewhere in eastern Africa and across the continent suggests that this broader distinction between the two periods is in fact widespread. We suggest that the Later Stone Age represents new short use-life and multi-component ways of using stone tools, in which edge sharpness was prioritized over durability.

Keywords: Behavioral evolution; lithic technology; Late Pleistocene; early *Homo sapiens*

1. Introduction

The Middle to Later Stone Age transition is a major threshold of human behavioral complexity, with the Later Stone Age (LSA) representing the last pan-African phase of prehistoric human behavior (Ambrose, 2002; Barton et al., 2016; Grove and Blinkhorn, 2020; MacDonald, 1997; Tryon, 2019; Villa et al., 2012; Will et al., 2019a). The Middle Stone Age (MSA) emerges from the Acheulean ~300 ka (Brooks et al., 2018; Deino et al., 2018), broadly contemporaneous with the earliest known *Homo sapiens* fossils (Hublin et al., 2017), and is typically characterized by stone tool assemblages that combine Levallois technology and the use of diverse retouched flake tool kits, often with a focus on pointed tool production. In contrast, the LSA has been associated with the appearance of standardized bladelet production and backing (Goodwin and van Riet Lowe, 1929), as well as bipolar flaking (Eren et al., 2013; Villa et al., 2012) and increased use of exotic lithic materials (Ambrose, 2002). Although the phases were originally defined on the basis of stone tool technology (Goodwin and van Riet Lowe, 1929), some definitions incorporate other aspects of material culture (Tryon, 2019; Tryon and Faith, 2016), such as ostrich eggshell beads, small bone points, and notched bones for the LSA (d’Errico et al., 2012b; Diez-Martín et al., 2009).

Changes in cognition, climate, population size and structure, social organization, and subsistence are variously invoked in explaining the MSA-LSA transition (Blome et al., 2012; Klein, 2002; Mellars et al., 2013; Powell et al., 2009; Tryon and Faith, 2016). These parameters and their relationship to Late Pleistocene material culture have been examined across Africa (Barton et al., 2016; Douka et al., 2014; Niang et al., 2018; Tryon et al., 2018), but with considerable emphasis placed upon southern Africa due to the large number of well-dated, rich archaeological assemblages there (d’Errico et al., 2012a; Mackay, 2010; Mitchell, 1994). Technological and cultural changes during the Late Pleistocene of eastern Africa are receiving increasing attention, in part because the region was likely a key nexus in the migration of *H. sapiens* beyond Africa (Groucutt et al., 2015). There is, however, considerable variance in the reported timing of LSA origins across eastern Africa (Tryon, 2019), with estimates of over 50 ka in the Rift Valley sites Enkapune ya Muto (Ambrose, 1998), Olduvai Gorge (Skinner et al., 2003), and Mumba (Gliganic et al., 2012), contrasting with MSA ages of less than 40 ka at sites in Ethiopia (Ossendorf et al., 2019; Pleurdeau et al., 2014).

Eastern Africa's lake records provide a regional perspective on the environmental background of the MSA-LSA transition that document substantial variability in precipitation across the Late Pleistocene (Lane et al., 2013). Such variability would have had major impacts on the structure and extent of grasslands, woodland, and forests throughout the Late Pleistocene, as well as the mammalian fauna they supported (Faith et al., 2015; Tryon et al., 2010). However, the majority of archaeological and paleoenvironmental evidence from eastern Africa is derived from the interior (Roberts et al., 2020). This has led to the late MSA and early LSA, as well as human dispersals out of Africa, being associated with expanding savannah grasslands (Tryon and Faith, 2016), with the innovation of efficient projectile technologies providing major benefits in the hunting of large mammalian fauna (Shea and Sisk, 2010). Higher latitude maritime habitats in southern Africa are thought to have provided plentiful high-protein and fatty marine resources for Late Pleistocene innovation and dispersal (Jerardino and Marean, 2010; Marean, 2011; Will et al., 2019b), although this is yet to be observed in an eastern African context. Evidence from high altitude, high latitude, tropical forest, and desert settings suggests that Late Pleistocene *H. sapiens* had highly varied environmental associations (Roberts et al., 2020; Roberts and Stewart, 2018), necessitating more context-specific approaches to technological change.

Here we examine, in detail, the stone artifact sequence from Panga ya Saidi, a stratified cave site 15 km from the coast of Kenya (Fig. 1) and ~500 km east of the Rift Valley. The cave site is unique in eastern Africa in having a punctuated but relatively continuous archaeological sequence spanning the last ~78 ka, including occupations in each of the last five Marine Isotope Stages (MIS), as well as complementary paleoenvironmental and occupation intensity proxies. The Panga ya Saidi sequence covers the final MSA and early LSA, presenting an opportunity to examine trajectories across these two phases, and, importantly, includes the oldest assemblage with LSA characteristics currently known in eastern Africa, dating to ~67 ka (Shipton et al., 2018). Moreover, the site is situated today within a narrow band of tropical forest in coastal Kenya, enabling assessment of the environmental and subsistence associations of MSA and LSA producing populations, in a habitat not frequently addressed by other studies (Basell, 2008; Blome et al., 2012). The site has also yielded biomolecular data on fauna and ancient DNA on human remains, allowing assessment of biological exchanges and genetic ancestry respectively (Prendergast et al., 2017; Skoglund et al., 2017; Wang et al., 2020). Here, we analyze the lithic technological sequence to determine the timing and persistence of key changes, and contextualize them in relation to changes in other artifact types (d'Errico et al., 2020), local ecology (Roberts et al., 2020), and the wider discussion of drivers of Late Pleistocene technological changes in Africa. Through focusing on the lithics we are also able to compare Panga ya Saidi more broadly with sites that lack organic preservation and environmental proxies (Blinkhorn and Grove, 2018; Grove and Blinkhorn, 2020). Against this backdrop of environmental proxies and organic artifacts, we aim to provide a stone artifact-based definition of what constitutes the LSA at Panga ya Saidi, allowing others to determine how widely applicable our model is elsewhere in Africa.

1.1. Identifying the Middle to Later Stone Age technological transition in eastern Africa

Despite the importance of the MSA-LSA transition, definitions of both these broad technocomplexes are contentious. General characterizations of MSA and LSA lithics, as presented above, offer a useful means to understand the wider structures of changing behavior in the past. However, they are less adept at examining behavioral change in higher resolution as they compress considerable variability in the archaeological record (Pargeter et al., 2018; Pleurdeau, 2005; Tryon, 2019; Tryon and Faith, 2013). Indeed, neither the MSA nor LSA has been readily defined by the ubiquitous presence of a single attribute in all assemblages; rather, they are polythetic entities composed of assemblages with overlapping constellations of key attributes (Lombard et al., 2012; Grove and Blinkhorn, 2020).

Definitions and descriptions of key MSA and LSA artifact types are provided in the Supplementary Online Material (SOM) S1. A recent quantitative study of the eastern African MSA has identified Levallois reduction methods, discoidal cores, retouched points, scrapers and denticulates as key typological components of stone tool assemblages (Blinkhorn and Grove, 2018). Studies of early LSA industries in eastern Africa have identified the dominant use of bipolar technology (Eren et al., 2013; Tryon and Faith, 2016) and the appearance of prismatic blade production and backed geometric pieces (Ambrose, 1998; Grove and Blinkhorn, 2020), which are also used to define early LSA industries in central (Mercader and Brooks, 2001), western (Cornelissen, 2003), and southern (Bousman and Brink, 2018; Goodwin and van Riet Lowe, 1929) Africa.

Importantly, the use of typological attributes to differentiate MSA and LSA industries is complicated by the presence of characteristic LSA types including bipolar technology, blade production, and backing within MSA assemblages (Blinkhorn and Grove, 2018; Tryon and Faith, 2013), and the persistence of MSA types, such as Levallois technologies, within LSA assemblages (Shipton et al., 2018; Tryon et al., 2018). The southern African MSA-LSA transition differs from that of eastern Africa in this respect, with the former broadly characterized by an abandonment of hemispheric flake production systems (e.g., Levallois, discoidal) and the predominance of bipolar and prismatic bladelet technologies that were only ephemerally present in the later MSA (Soriano et al., 2007; Villa et al., 2012). Proportional rather than categorical change may be a better way of characterizing the technological changes of the MSA-LSA transition (Tryon, 2019; Tryon et al., 2018), although identifying suitable proportional thresholds may not be straightforward.

A further trait change that has been used to define the MSA-LSA transition is the use of alternate rock types, in particular siliceous and exotic stone (Ambrose, 2012; Leakey et al., 1972; Shipton et al., 2018). Pargeter and Shea (2019) have emphasized size reduction in siliceous lithics as a major trend through time, and noted that in eastern Africa this size change appears decoupled from patterns of artifact typology. Some eastern African studies have highlighted a decrease in artifact size as a means to discriminate between MSA and LSA assemblages (Brandt and Gresham, 1990; Leakey et al., 1972; Shipton et al., 2018). In southern Africa, a tendency to produce small stone artifacts is also evident in early LSA assemblages, such as at Border Cave (Villa et al., 2012), Rose Cottage Cave and Uhmlatuzana (McCall and Thomas, 2009), and Erb Tanks (McCall et al., 2011).

Modeling of the formation of lithic artifact assemblages indicates particular traits track hominin mobility. In situations of high mobility there should be a need to resharpen tools through retouching more frequently; since flaking is taking place at multiple locations, artifact density at any individual site will be low, but the proportion of cores relative to flakes will be high; there may also be investment in more formal technology to maximize the use-life of cores and generate more predictable flake products; and there will likely be greater proportions of more distantly sourced materials (Barton and Riel-Salvatore, 2014; Kuhn, 1992, 1994; Parry and Kelly, 1987; Wallace and Shea, 2006). Conversely, in situations of low mobility, there should be low proportions of cores and retouched flakes, high proportions of local material, high artifact density, and less formal technology. These different expectations in regards to mobility are sometimes dichotomized as person provisioning, in which artifacts are curated by mobile individuals; and place provisioning, in which local material is knapped at a frequently used site.

Differences in the presence-absence or proportional representation of alternate lithic technologies, types, materials, and size, together offer useful indices to identify changes in behavior associated with the MSA-LSA transition. However, the isolated appearance of any one of these features may be insufficient grounds to identify a substantive change in behavior. Rather, there is a need to not only identify the nature and timing of these changes, but also the constellations of other features in which they occur, and their persistence in the archaeological record.

The appearance of a new technological behavior at a site may result from independent innovation, cultural diffusion, or demic expansion (e.g. Archer et al., 2021; Bousman and Brink, 2018; Powell et al., 2009). Explaining why the transition from the MSA to LSA occurred in a given context thus requires reference to the potential significance of local demography and ecology. Panga ya Saidi offers a combination of dated archaeological assemblages spanning the Late Pleistocene that are associated with a rich paleoenvironmental archive and several proxies for occupation intensity (Roberts et al., 2020; Shipton et al., 2018). These allow for the examination of directional patterns in behavioral change across the MSA-LSA transition.

The present study investigates diachronic variability in lithic indicators of the MSA and LSA in the Panga ya Saidi sequence. These indicators include Levallois reduction, a key element of MSA industries, and the appearance of artifact types indicative of LSA technologies, including backing, bipolar and prismatic blade reduction. A further goal of the analysis is to explore the phenomenon of lithic miniaturization, the preferential creation of small fine-grained (highly siliceous or cryptocrystalline) lithics (Pargeter, 2016). Miniaturization was proposed by Shipton et al. (2018) to be a key feature distinguishing the LSA from the MSA assemblages at Panga ya Saidi, so we record rock type, a number of lithic size parameters, as well as indices of reduction intensity. We also ascertain through surveys the degree to which different rock types represent local or distal provisioning. We examine these lithic variables alongside the environmental sequence to determine which aspects of technology may be related to adaptation to changing environments, and which aspects are less contingent on behavioral trends.

1.2. Site and environment

Panga ya Saidi is a large cave complex in the Jurassic Kambe limestone formation (Caswell, 1956) that forms the Dzitsoni ridge running parallel to the coast. Overlying the limestone in many places is the Margarini Sands formation: a diachronous deposit of bright red sands and ferrallitic soils that may date from the Late Pliocene to the Late Pleistocene (Caswell, 1956; Oosterom, 1988). The gently sloping surface extending east of the Dzitsoni ridge between the altitudes of 110 and 60 m, was formed on Upper Jurassic to Lower Cretaceous yellow shales, marls, limestones, sandstones, and cherty mudstones, grading upwards into fossiliferous shales (Caswell, 1956; Gregory, 1921).

The main excavation at Panga ya Saidi is located just inside the east entrance to the cave (Fig. 2A). A single, contiguous excavation has been undertaken across four field seasons (2010, 2011, 2013, 2017), with individual interventions labelled as Trenches 1 and 3-8 (SOM Fig. S1). A second, non-contiguous excavation was undertaken elsewhere at the site (Trench 2; Fig. 2A), from which no material is included in this study. To estimate sediment volume, filled 10 L buckets of sediment from each excavation context were counted. The bulk of excavated material was dry sieved on site through a 5 mm^2 mesh. 60 L samples from each layer of Trenches 1, 3, and 4, as well as total samples of smaller features, were floated and wet sieved off-site through a 1 mm^2 mesh. In total for Trenches 1, 3, and 4, 14.4% (1868 L) of the excavated sample was wet sieved.

The Panga ya Saidi sequence is comprised of 19 layers, which, except for Layers 7 and 12, are continuous across the main excavation and thus consistent between trenches. Layers are numbered from top to bottom, with Layer 1 dated to the last 0.5 ka while Layer 19 is estimated to have been deposited >78 ka (Fig. 2B; Shipton et al., 2018). Conjoining of ancient lithic artifact breaks within layers (SOM Fig. S2) and the presence of laterally traceable ash and other paleofloor deposits (from Layer 13 upwards) testify to the stratigraphic integrity of the site. The layers form the basic unit for the following analyses, with excavation contexts from each trench assigned to a layer. Three new radiocarbon dates from the 2017 excavation are reported here, in addition to the 21 radiocarbon and optically stimulated luminescence (OSL) ages reported in Shipton et al. (2018; see Tables 1 and 2). The new ages were calibrated with OxCal 4.4 (Bronk Ramsey, 2009) and the Intcal20 calibration curve (Reimer et al., 2020). These ages show that Layer 7 dates to the Last Glacial Maximum (LGM), and confirm the latest Pleistocene age of Layer 5 and the early Holocene age of Layer 4. For the ages of Layers 8–18 reported throughout this article we use the Bayesian model from Shipton et al. (2018) and the centroid of the modelled layers or layer boundaries. The critical transition in the Panga ya Saidi sequence, suggested to represent the transition from MSA to LSA, was across Layers 17 and 16, with this layer boundary dated to between 72 and 67 ka (Shipton et al., 2018). A sharp decrease in χlf paleomagnetic values in the upper part of Layer 17 likely corresponds to the climatic change of the MIS 5–4 transition (Shipton et al., 2018).

2. Materials and methods

The Panga ya Saidi lithics are curated at the National Museum of Kenya (NMK) in Nairobi. The lithics are stored under the site code PYS with three-digit excavation context numbers—the first of which denotes the trench. Letter suffixes denote subdivisions of thicker contexts.

The lithics analyzed here derive principally from contiguous Trenches 1, 3, and 4, as these trenches have been subject to the most comprehensive paleoenvironmental analyses undertaken so far (Roberts et al., 2020; Shipton et al., 2018). Additional information on lithics is also included from contiguous Trenches 5–8 to increase sample size for some analyses.

For several analyses of particular lithic classes, layers are grouped according to age to increase sample size, consistent with their grouping for faunal analysis by Roberts et al. (2020) to ensure compatibility of the analyses. Layer groupings are as follows: 19–17 (78–72 ka, late MIS 5), 16–13 (67–54 ka, MIS 4), 12–11 (54–48 ka, early MIS 3), 10 (48–40 ka, mid MIS 3), 9 (40–29 ka, late MIS 3), 8–7 (29–20 ka, LGM), 6–5 (14.5 ka, latest Pleistocene), 4 (8 ka, middle Holocene), and 3–1 (1–0.5 ka, late Holocene).

Three stone types were predominantly used for making lithics at Panga ya Saidi: quartz, limestone, and chert. To determine the local distribution of these materials, we conducted a targeted survey in a 10 km radius around the cave. We used geological maps (Caswell, 1956) and satellite imagery to provide an overview of the major geomorphic features of the area, then focused on high-potential areas identified by local people who had in-depth knowledge of the landscape and were familiar with the types of stone used for artifact manufacture at Panga ya Saidi.

The flaked stone artifacts from Panga ya Saidi were first classified, counted, and weighed according to rock type and fundamental technological class: cores, debitage (including complete flakes, broken flakes, and indeterminate pieces), retouched flakes. The data presented here for the count and classification includes the material from all four seasons of excavation at Panga ya Saidi, and allows us to determine if the previously identified pattern in rock type selection (Shipton et al., 2018) holds with the larger sample size provided by Trenches 5–8. Lithic density by layer was calculated in two ways: firstly, by dividing the total number of lithics for each layer by the volume of excavated sediment; secondly, by dividing total lithic weight by the volume of sediment excavated. Measuring density in these ways allows for comparisons between assemblages where fewer longer cutting edges on heavier artifacts were performing cutting tasks with those where many shorter cutting edges on lighter artifacts were used. At Panga ya Saidi this is important given the reported difference in artifact size between Layers 19-17 and 16-1 (Shipton et al., 2018).

The 5 mm^2 sieve mesh biases the assemblage against very small flakes (3–4 mm long) that are known to occur in miniaturized assemblages elsewhere (Maloney et al., 2018; Pargeter, 2016; Shipton et al., 2019). To test for miniaturization down to these small flake sizes, we recorded mean debitage weight separately for those flakes that were recovered from the 1 mm^2 wet sieve from Trenches 1, 3, and 4.

Variables were recorded to distinguish between different reduction strategies, in particular Levallois and prismatic blade, which have been central to definitions of MSA and LSA technology respectively. Details of these standardized qualitative and metric attributes are presented in SOM S2. Cores and their main platforms were assigned to types, and the number of blade scars on each core was counted. Flake platforms and dorsal scar patterns were similarly assigned to types. Flake axial (box) length and medial width were measured to calculate elongation and determine whether there was systematic production of blades. The presence of any platform preparation on cores and flakes was noted. Flakes with crushed platforms and terminations were classified as bipolar, while elongate (longer than they are wide) flat flakes with prepared platforms and <10% cortex were classified as Levallois. To elucidate the size and form of retouched flakes these were assigned to types, and their length, width, and thickness were measured. To explore the impact of reduction on flake size two measures of reduction intensity were used: the percentage of cortex coverage was estimated to the nearest 10%; and the number of scars struck prior to the flake itself (i.e., not initiated from nor struck onto, the ventral surface) were counted and divided by the product of axial (box) length and medial width (Dogandžić et al., 2015), to calculate the scar density index (SDI; Clarkson, 2013).

The above variables were recorded on all cores and retouched flakes from Trenches 1, 3, and 4, but due to the high volume of debitage, these variables were only recorded on limestone and chert flakes larger than 25 mm and quartz flakes larger than 20 mm from Trench 4. Trench 4 was chosen as it is the only trench that samples the entire vertical profile of the sequence, giving us a technological perspective on unretouched larger flakes throughout the occupation history of Panga ya Saidi. Two different size thresholds were used as quartz flakes are in general much smaller than chert and limestone. Using different cut-offs samples comparable proportions of all three materials, rather than biasing towards one material or the others. The rationale behind examining larger flakes is that these tend to preserve relatively higher numbers of previous flake scars on their larger surface area, and, while they are biased towards the earlier stages of reduction, concomitant analysis of the cores provides information on the final removals of the reduction sequence. The handful of flakes on materials other than limestone, quartz, or chert, were all measured. To increase the sample size of one key but rare artifact type, we also measured all Levallois flakes from Trenches 5–8.

The transition from the MSA to the LSA at Panga ya Saidi was identified, on the basis of miniaturization, across Layers 17 to 16 (72–67 ka; Shipton et al., 2018). Given the importance of these two layers, all artifacts from Layers 17 and 16 were weighed, and axial length, medial width, and medial thickness were measured on all complete flakes (including those from Trenches 5–8). To further expand the sample size either side of this transition, all debitage pieces from Layers 15 and 18 were also individually weighed.

Our aim with this analysis is to examine the critical Layer 17–16 transition in detail and place it in long-term context by examining material selection, lithic size, and technology throughout the sequence. We use a combination of parametric and non-parametric statistics, depending on sample size and distribution of the variables in question, to test for significant differences between artifact population central tendencies. In particular, we use equal and unequal variances t-tests (for two large normal populations), Mann-Whitney U tests (for two small and/or non-normal populations), one-way ANOVAs (for testing between three or more large normal populations), and Kruskall-Wallis tests (for testing between three or more small or non-normal populations). A general linear model (GLM) is used to explore the effects of both quantitative and qualitative variables on reduction intensity. We use chi-square tests to determine if differences in the proportion of qualitative variables are significant. Statistical tests were performed in SPSS (IBM Corp, 2017) and R (RCoreTeam, 2017).

3. Results

3.1. Local stone sources

Here we describe the results of our lithic sourcing survey to provide the provisioning context for the stone artifacts described in subsequent sections. We focus on the three main rock types that comprise over 99% of lithic artifacts made by the Panga ya Saidi knappers: limestone, quartz, and chert.

The Kambe limestone on the seaward (east) side of the Dzitsoni ridge, in which the cave occurs, is coraline and oolitic, making it unsuitable for knapping. However, on the landward side of the ridge the limestone is non-fossiliferous, homogenous, and hard enough to be knapped into stone tools. These properties have also made this landward limestone facies attractive to intensive modern quarrying, so any traces of prehistoric activity there have been obliterated. The nearest of these modern quarries occurs 1.5 km WNW from Panga ya Saidi as-the-crow-flies (Fig. 3). Limestone would have outcropped on the surface here and elsewhere along the west side of the ridge prior to quarrying (SOM Fig. S3). Clasts of this limestone facies on the surface often exceed 500 mm in maximum dimension.

The inland part of the Magarini Formation that overlies the limestone in the vicinity of Panga ya Saidi consists of detrital material derived from all older lithified deposits; including well-rounded pebbles of limestone, sandstone, and various types of quartz, and abundant quartz sand. The Magarini Sands (Fig. 3) have undergone extensive ferralitic weathering, which has given them their characteristic red colour and resulted in deposits of iron/manganese pisoliths that are today mined by hand as iron ore. At such a mine about 0.7 km south of Panga ya Saidi on the Dzitsoni ridge, there are piles of quartz pebbles that have been left as waste by the miners (SOM Fig. S3). The pebbles, which are up to ~50 mm in maximum dimension, include both the milky and clear crystal quartz varieties represented in the Panga ya Saidi lithics. Fresh artifacts, such as bipolar cores, also occur in the waste piles (SOM Fig. S4), indicating that this source of quartz was both available to, and exploited by, prehistoric populations. Another iron ore mining tail deposit of quartz pebbles with artifacts was located 3.5 km south of the cave, though there the pebbles were smaller and the artifacts less numerous.

Within the shale beds that underlie the 60–110 m surface seawards of the cave (Fig. 3), small silicified nodules of mudstone (‘chert’) occur. These are green in color in the center, becoming yellowish near the cortex. An informal experiment indicated that when heated, this stone turns red, as is observed on some of the Panga ya Saidi lithics. Shales with these siliceous mudstone nodules are exposed at modern road cuttings on the surface east of the Dzitsoni ridge, but their natural surface exposure is minimal. At the confluence of two seasonal stream tributaries of the Kilifi Creek, about 4.8 km from Panga ya Saidi, a meander has eroded into the shale beds on its outer bend, depositing numerous clasts of siliceous mudstone on the following inner bend (SOM Fig. S3). At this location, we found unmodified siliceous mudstone clasts up to ~100 mm in maximum dimension as well as several artifacts in both fresh and slightly rounded condition, including a Levallois core (SOM Fig. S4). No other chert/siliceous mudstone sources were encountered during survey. The chert of the Panga ya Saidi lithics is relatively homogenous in appearance, suggesting that it all derives from the same source. Given the scarcity of natural exposures of the shale beds, and the rarity of silicified nodules within them, it seems that this meander would have been the nearest reliable source of chert to Panga ya Saidi. The meander would have migrated during the course of the Late Pleistocene, but as it is close to the headwaters and just downstream from the confluence of two streams, we infer that its migration has been minimal. Upstream from this, the valleys are much smaller and lack extensive alluvial deposits. Notably, this potential chert source is in the direction of the Kilifi Creek lagoon, which at its nearest is about 8.6 km from Panga ya Saidi today. Across the landscape, including the Kilifi Creek, there would have been more fluvial incision during the low sea-level stand of MIS 2 which likely would have exposed and accumulated more chert nodules.

Other rock types represented among the Panga ya Saidi lithics include quartzite, silcrete, and chalcedony. However, these occur in very low numbers: 46 pieces, 0.1% of the total assemblage. Since no sources of these rock types were encountered in our survey of the 10 km around the site, they are presumed to be exotic imports.

An additional finding of the survey was the nearest permanent water source (in the present climatic conditions): a perennial river, 5.3 km northwards that feeds the Kilifi Creek. Due to the porous nature of the Kambe limestone, surface water is unavailable in the vicinity of the cave in the dry season. Local residents testified that before wells were dug, people used to travel to collect water from this perennial river in the dry seasons.

Limestone and quartz are common in parts of the landscape, with the nearest sources 1.5 km north-westward and 0.7 km southward respectively. Chert is less abundant, with the nearest identified source 4.8 km north-eastward. The three main rock types used for artifact production at Panga ya Saidi are thus all local, but quartz and limestone were easier to access than chert.

3.2. Lithic materials, frequency, and size

In total, over the four seasons of excavation (Trenches 1 and 3–8), 46,434 lithic artifacts weighing 101.45 kg have been recovered from Panga ya Saidi. Discounting hammerstones, grindstones, and artifacts from intrusive contexts, we are left with a flaked assemblage of 44,920 pieces attributed to the 19 layers (Table 3). The majority of these lithics by count are quartz (64.9%), followed by chert (23.5%) and limestone (11.5%), with a very small proportion of exotic pieces (0.1%). These rock types are unevenly distributed through the sequence with limestone dominant in the lower three Layers (17–19), while quartz and, to a lesser extent, chert are dominant for the remainder of the sequence (Layers 1–16; Fig. 4). A chi-square test showed that the difference in rock type frequency between Layers 17 and 16 was significant at $p < 0.00001$ ($n = 582$, $\chi = 235.7$).

Lithic density peaks in Layers 19–18, 14, 12–11, and 8–7, while Layers 17–16 and Layers 2–1 represent pronounced troughs in density (Table 3). Layers 1 and 2 date to the last 1000 years when lithics were being replaced by iron in this part of the eastern African coast. The paucity of lithics in Layers 17 and 16, suggests that this was a time of low occupation intensity. In particular, the upper 30 cm of Layer 17 contains very few lithics (*n* = 41), but their consistent presence suggests this may not have been a complete occupational hiatus.

A further contrast between Layers 17 and 16 is the difference in debitage weight. Figure 5 shows mean debitage (complete flakes, broken flakes, and indeterminate fragments) weight by layer, with relatively large lithics in Layers 19–17, a sharp drop between Layers 17 and 16, and small lithics through the rest of the sequence. To test the significance of this pattern, we performed a t-test on individual artifact weights for all debitage from Layers 16 and 17. The results indicate a highly significant difference between the layers (Table 4). An obvious potential reason for this difference in weight is the difference in dominant rock types across the Layer 17–16 boundary, as limestone is available in much larger clasts than quartz and chert. To test for this, we conducted two individual t-tests on quartz and chert, and on limestone debitage (Table 4). The results show that there is no reduction in the size of limestone across this stratigraphic boundary, but quartz and chert artifacts in Layer 16 are significantly smaller than in Layer 17. Another possibility is that this difference in lithic size is driven by differences in rates of fracture. To test for this, we conducted t-tests of complete flake weights for all artifacts, and for quartz and chert only (Table 4). The tests showed significant differences in both cases indicating that the difference in artifact size across the Layer 17–16 boundary was not driven by differences in degree of artifact fragmentation.

To test for the broader persistence of the reduction in size beyond the Layer 17–16 transition itself, we included debitage weight from Layers 18 and 15 in the comparisons, with the results replicating the above patterns (Table 4). This broader sample was also able to show that when quartz and chert are considered separately, both as all debitage (Fig. 6) and complete flakes, there are significant differences in size across the Layer 17–16 transition (Table 4). We further looked at the difference in complete quartz and chert flake area (length × width) across the Layer 17–16 transition. An unequal variances t-test showed that this difference was significant at $p < 0.001$ (df = 57.8, mean difference = 208.5 mm^2, t = -4.242). Mean complete flake length (all materials) for Layer 17 is 26.17 ± 11.8 mm vs. 19.96 ± 6.42 mm for Layer 16. Again, an unequal variances t-test showed that this difference was significant at $p < 0.001$ (df = 268.826, mean difference = 6.21 mm, t = 5.609).

To test the effect of the missing fraction of very small flakes from the 5 mm^2 dry sieve mesh, we examined mean debitage weight for the sample of lithics recovered from the wet sieving only (n = 8390), where mesh size was 1 mm^2. The results (SOM Fig. S5) replicate the pattern shown in Fig. 5, but show an even more pronounced dichotomy in size with mean debitage weight >2 g for Layers 19-17 and <1 g for Layer 16 and above.

At a time of very low artifact density across the Layer 17–16 boundary there was a significant shift from limestone to quartz and chert as the dominant materials, and a concomitant reduction in the size of chert and quartz artifacts (SOM Fig. S6). Both these attributes then persisted throughout the rest of the sequence.

3.3 Core reduction

There are 662 cores in the Panga ya Saidi assemblage, with their distribution by layer shown in Table 3 and Figure 7. Peaks in core frequency occur in Layers 16, 13–11, and 3–1, with a trough in Layer 17 (although it should be remembered that sample sizes are small for Layers 17 and 16).

The 393 cores from Trenches 1, 3, and 4 were assigned to technological types (Fig. 8). There is a clear correspondence between the type of rock knapped and the reduction strategy used (Table 5). The great majority of cores are quartz, including nearly all of the assayed (tested, but not extensively flaked cores), bipolar (Fig. 9; SOM Fig. S7), and single-platform pieces. The more formal types, Levallois and prismatic, are typically made on chert. Limestone cores are rare, and several of those recovered are bipolar (Fig. 9). Limestone cores have low SDI values, appearing to be markedly less reduced than the other two rock types, but the number of limestone cores is too small to test this statistically. A Mann-Whitney U test showed no significant difference in scar density between quartz and chert (n = 354, U = 6473, p = 0.734). A one-way ANOVA test also showed no difference in scar density between core types (excluding assayed cores, which by definition have low scar densities, and prismatic cores, for which sample size was too small; df = 298, F = 1.883, p = 0.113).

Several trends in the key core types are apparent in this data: Levallois cores occur at three points in the sequence, Layers 19, 12–10, and 6–1, separated by multiple layers of absence; prismatic cores also occur sporadically through the sequence in Layers 13, 8, and 4; bipolar cores are common from Layer 16 upwards, representing over half of the cores in Layers 16–13 and 8–7; yet they are absent from Layer 10. The Levallois cores from the three parts of the sequence where they are represented are distinct: that from Layer 19 is large and centripetally flaked; in Layers 12–10 they are small centripetal pieces; and in Layers 6–1 they are larger with parallel flaking (Fig. 10).

Low proportions of blade scars occur on cores from Layers 19–17 and 12–10, while there are peaks in Layers 16–13 and 8–4 (SOM Fig. S8), where prismatic blade cores also occur (Fig. 8; SOM Fig. S9). A Kruskall-Wallis test confirmed that there was significant heterogeneity between phases in the proportion of blade scars on cores (H = 22.302, df = 8, p = 0.004).

3.4 Flakes

A sample of 1094 large and exotic flakes were measured from Trench 4. As for cores, there is a clear correspondence between rock type and technology, with 53% of the large quartz flakes but none of the chert flakes being bipolar (Table 6). Conversely, 5% of the chert flakes are Levallois, while only a single quartz flake is of this type (SOM Fig. S10).

Excluding exotic pieces, flakes of chert, the highest quality local material, have the highest scar densities. These are followed by quartz, then limestone, which comes in the largest packages with the least need to maximize productivity through increased reduction intensity (SOM Fig. S11). A one-way ANOVA test confirmed that these differences in SDI between rock types were significant (df = 777, F = 36.839, $p < 0.001$). Redirecting flakes to prolong the life of a core are more prevalent on chert than on the other materials (Table 6). Across the sequence, redirecting flakes are common from Layer 8 upwards, as well as in Layers 12–11, but are absent from Layer 9 (Table 6).

Over one third of the large flakes are bipolar in Layers 16–13 and 8–7, those layers in which bipolar cores are particularly prevalent (Table 6). Bipolar flakes are also common in Layer 9; and notably, they are also present in Layers 19–17 and 10 where no bipolar cores are found. In Layers 19–17 however, bipolar flakes only constitute 2% of the large flake assemblage.

Levallois flakes occur sporadically through much of the sequence, including Layers 16–13 and 8–7 where there are no Levallois cores, but they are absent in Layer 9 (Table 6). Levallois flakes were most frequent in Layer 10 where the highest proportion of Levallois cores was recorded. Levallois products from different parts of the sequence were distinct: in Layers 19–17 Levallois flakes are large, while in the layers above they are much smaller, with examples of parallel sided blades in Layers 4 and 5 (Fig. 11). By including Levallois flakes from Trenches 5–8, we were able to statistically compare their dimensions between Layers 19–17 and higher up the sequence (SOM Fig. S12). The contrast in size is stark: Levallois flakes from Layers 19–17 are significantly longer, wider, and thicker, and with wider platforms than those from higher up (Table 7).

In general, flake elongation is low in Layers 19–17, rises sharply in Layer 16, then drops in the middle of the sequence (Layers 13–9), before a modest rise in Layers 8–3 (SOM Figs.

S13 and S14). Unequal variances t-tests confirmed significant differences between Layers 19–17 and 16–13, Layers 16–13 and 12–9, and Layers 12–9 and 8–1 (Table 8). Focusing on the early part of the sequence, a violin plot (Fig. 12) shows the difference in flake elongation between Layers 19–17 and Layers 16 to 12, with a unimodal distribution for the former, and a bimodal distribution, reflecting the addition of a blade component, in the latter.

Platform types by layer(s) are shown in Table 9. Crushed platforms are particularly prevalent in Layers 16–13 and 8–7 as a consequence of bipolar flaking. Both overhang removal and facetting are evident throughout the sequence. These platform preparation techniques are concentrated on the higher quality chert and exotic stone; they occur sporadically on limestone and rarely on quartz. There are high levels of platform preparation in Layers 19–17, 12–10, and 6–1, which feature the formal technologies of Levallois or prismatic blades. Conversely, there are low levels of platform preparation in Layers 16–13 and 9–7, where the less formal bipolar technique dominates.

Dorsal scar patterns were grouped into the following categories: cortical, parallel (comprising proximal, distal, and bidirectional patterns), and non-parallel (comprising lateral, orthogonal, and radial patterns). Table 10 shows a high proportion of non-parallel flaking in Layers 19–17; a high proportion of parallel flaking in Layers 16–13; low proportions of cortical flakes and relatively high proportions of non-parallel flaking in Layers 12–10; high proportions of cortical flakes in Layers 9–7; and high proportions of parallel flaking in Layers 6–1. A chi-square test showed the difference between these five groups to be highly significant ($\chi = 36.247$, $p < 0.001$).

Even for flakes longer than 25 mm, complete pieces from Layers 19–17 were significantly larger in area (axial length × medial width) than those from both the immediately overlying layers 16–13 (df = 252.191, mean difference = 667 mm^2, t = 10.442, $p < 0.001$), and the entire overlying sequence (df = 224.67, mean difference = 385 mm^2, t = 6.419, $p < 0.001$) (Table 5).

The difference in large flake size may be partially explained by reduction intensity. Flakes from Layers 19–17 have less cortex than any of the succeeding phases until the Holocene (Table 6; SOM Fig. S15), indicating that lower reduction intensity is unlikely to be driving the difference in large flake size. However, Layers 19–17 also have relatively low SDI values compared with many of the other phases. This likely reflects the larger initial clast sizes of the limestone dominant in this phase of occupation, as larger clasts will have a higher cortex to volume ratio, so more non-cortical flakes can be produced for a given degree of reduction intensity (Table 6; SOM Fig. S15). To explore the effect of reduction intensity on flake size, a Mann-Whitney U test compared the SDI of flakes longer than 25 mm (Table 6) from Layers 19–17 with that of flakes from the overlying sequence. The test suggests that the relatively low scar density in Layers 19–17 is not markedly different from that in the layers above (n = 693, U = 40052.5, $p = 0.16$). When limestone flakes, which are significantly less reduced, were removed, there is no difference between Layers 19–17 and the rest of the lithic assemblage (n = 450, U = 7229.5, $p = 0.766$). To further explore the effect of reduction intensity, we conducted a GLM of the relationship between large flake weight and SDI with the layer grouping (19–17 vs. 16–1) and rock type as fixed factors. The analysis showed that there was a significant but weak relationship between SDI and weight (n = 689, F = 21.31, $p < 0.001$, $R^2 = 0.18$), with a significant but weak effect of rock type (F = 8.85, $p < 0.001$, partial $H^2 = 0.038$), and no effect of layer grouping (F = 1.105, $p = 0.294$, partial $H^2 = 0.002$). This indicates that smaller flakes do occur when reduction intensity is higher, but the limited effect is driven partly by differences in material and not by differences between layer groups.

3.5 Retouched flakes

Only 228 (<1%) of the 44,920 lithics from Panga ya Saidi are retouched flakes. Of these, 186 (81%) are chert, 18 (8%) are quartz, 18 (8%) are limestone, and 6 (3%) are exotic. Moderate levels of retouch occur in Layers 19–17; retouch then disappears entirely in Layers 16–14, picks up again in Layers 13–11, before dropping to very low levels in Layers 10–7 (Table 3; Fig. 13). Retouch becomes more frequent in Layers 6–5, and reaches its highest levels in Layers 4–1 (Table 3; Fig. 13).

Retouched artifacts from Trenches 1, 3, and 4 were assigned to types and measured. Retouch is characterized by different artifact types through the sequence (Table 11). In Layers 19–17 large Levallois flakes were retouched (Fig. 14). In Layers 12–11 backed crescents appear alongside marginally retouched blades (Fig. 15). Backed artifacts then disappear from the record between Layers 10 and 7. In Layer 6–1 crescents reappear alongside trapezoidal and occasionally triangular backed forms (Fig. 15).

Retouched flakes from Layers 19–17 are considerably larger than those from the rest of the sequence, with Mann-Whitney U tests indicating significant differences in size across weight, length, width, and thickness (Table 12). This pattern also holds true when backed artifacts are excluded (Table 12). Considering only those artifacts with retouch on the working edges (as opposed to the hafting modification of backing), these are significantly more frequent in Layers 19–17 (0.9%) than in the rest of the sequence (0.218%) for Trenches 1, 3, and 4 ($\chi = 21.703$, $n = 27456$, $p < 0.00001$). This holds true even when Layers 19–17 are compared to individual phases with relatively high proportions of retouch, such as Layers 12–11 (0.439%) ($\chi = 4.234$, $n = 7170$, $p = 0.0396$) and Layers 4–1 (0.3%) ($\chi = 6.546$, $n = 4233$, $p = 0.0105$).

4. Discussion

4.1 The Panga ya Saidi lithic sequence in context

The three main knapped rock types from Panga ya Saidi were treated very differently by the site's occupants. Limestone, which occurs in larger packages (>100 mm in maximum dimension) but produces less sharp edges than the other two materials, was usually knapped without applying more formal strategies: limestone Levallois and redirecting flakes are therefore scarce (Table 6). No assayed limestone clasts were found (Table 5), likely due to the high transport costs of large packages. Reduction intensity, as measured by scar density on the dorsal surface of large flakes, was low for limestone, perhaps because the availability of large packages meant that there was little need to maximize core use-lives (SOM Fig. S11; Table 6). Assayed clasts are almost all quartz (Table 5), probably due to the minimal costs of transporting small quartz pebbles from proximal sources. Bipolar flaking was used mostly on quartz, with over half of the larger quartz flakes being bipolar (Table 6), as this knapping strategy is well-suited to knapping small clasts (<50 mm in maximum dimension). Nearly all formal reduction strategies of Levallois and prismatic blades, as well as instances of platform preparation, were on chert (Tables 5 and 6): a material that produces very sharp edges and is available in medium-sized packages (50–100 mm in maximum dimension). Over 80% of artifacts selected for retouch are on chert; this material also has the highest proportion of redirecting flakes and the highest scar densities on the dorsal surfaces of large flakes (SOM Fig. S11). This manifests the utility of chert and the long reduction sequences chert packages underwent. The need to employ curation strategies may have arisen from the more distant provenance and relative scarcity of chert (Fig. 3). The rare exotic flakes are small, with high scar densities, and high proportions of platform preparation and retouch (Table 6). Exotics occur sporadically through the sequence in Layers 18, 15, 13–11, 8–7, and 1 (Fig. 4), with no evidence for a unidirectional trend in their presence or relative abundance.

To contextualize the lithic technological changes at Panga ya Saidi, we examine the patterns in the stone artifact assemblage in relation to complementary evidence from other classes of material culture and environmental proxies. Much of the Panga ya Saidi sequence conforms to expectations of a place provisioning or logistical mobility strategy in which the site was used as a long-term base camp and stone clasts were imported for on-site knapping, producing relatively high artifact densities and low rates of retouch (Barton and Riel-Salvatore, 2014). This accords with the overall inference from the paleoenvironmental evidence of a persistent ecotonal environment around the site, suitable for long-term occupation (Roberts et al., 2020). There are three exceptions to this pattern, in the early, middle, and late parts of the sequence, which we discuss below.

Table 13 summarizes the key attributes of the Panga ya Saidi lithic assemblage by occupation phase. The initial occupation at Panga ya Saidi (Layers 19–17, 78–72 ka, late MIS 5), is typical of penecontemporaneous eastern African MSA (Blinkhorn and Grove, 2018; Tryon and Faith, 2013), with moderate sized Levallois cores, flakes, and retouched flakes (Figs. 10, 11, and 14). Although no bipolar cores were recovered, a few bipolar flakes (Table 6) indicate the occasional use of this technique. Dorsal surfaces on large flakes have the highest proportion of non-parallel scars from anywhere in the sequence (Table 10), indicating centripetal reduction patterns and a lack of systematic blade production. Blades, manifesting themselves either as scars on cores or as elongated flakes, are rare (SOM Figs. S8 and S13). Retouched flakes are relatively common and include large Levallois pieces (Fig. 14), but no backed artifacts.

While the technology of the initial occupation at Panga ya Saidi was not substantially different from contemporaneous and older sites in the region, the environmental setting of the site was distinct. A clayey sediment texture and a high diversity of terrestrial mollusc species in Layers 19–17 (78–72 ka, late MIS 5), indicate a humid, forested environment around Panga ya Saidi (Shipton et al., 2018). High magnetic susceptibility (χLF) values in Layer 18 and the lower part of Layer 17 suggest deposition in conditions warmer than at any subsequent point in the sequence (Fig. 16). The zooarchaeological assemblage of Layers 19–17 is dominated by browser and frugivore species of bovids and primates, respectively, while isotopic analysis of a subset of these faunal elements shows a preference for forest and woodland habitats (Fig. 16; Roberts et al., 2020). This clear use of tropical forest resources sets Panga ya Saidi apart from other eastern African MSA sites (Blinkhorn and Grove, 2018), and indeed sites of this age in general (Roberts and Petraglia, 2015). Layers 19 and 18, with relatively high levels of retouch and artifact density, depart from the standard inverse relationship between these two parameters along which most Paleolithic assemblages vary (Barton and Riel-Salvatore, 2014). This pattern may reflect relatively intensive bouts of occupation within a broader residential mobility strategy, with the site perhaps used as a seasonal aggregation camp.

Layer 17, particularly in its upper portion, is characterized by the lowest density of lithics in the sequence (Table 3), suggesting limited human occupation. At this stratigraphic level, magnetic susceptibility values show a rapid decline (Fig. 16) and the sediment becomes markedly sandier, culminating in a short-lived depositional hiatus between Layers 17 and 16. These signals are interpreted as evidence for cooling and drying at the MIS 5–4 transition (Shipton et al., 2018).

Following this transition, Layers 16–13 (67–54 ka, MIS 4) show an increase in lithic density, corresponding with increasing magnetic susceptibility, increased charcoal frequency, and increased point counts of (largely human-mediated) biogenic material in micromorphology samples, suggesting generally more intensive occupation from this point upwards (Shipton et al., 2018). Other environmental proxies, such as coarser sediment overall, and higher and more varied mammal teeth stable isotope values (Fig. 16), indicate that a drier, more markedly ecotonal environment, including ample grassland presence, developed around the cave from Layer 16 (Roberts et al., 2020). The lowest magnetic susceptibility measurements in Layer 16 followed by gradually increasing values during this period (Shipton et al., 2018) suggest warming climates through MIS 4, transitioning to more stable values at the transition to MIS 3 from Layer 13. Phytoliths, preserved from Layer 13 upwards, confirm the ecotonal character of the environment around the cave in the upper part of the sequence, with consistent presence of grass, alongside palm and woody species (Shipton et al., 2018).

Layer 16 at Panga ya Saidi sees the introduction of a marine shell (*Conus* sp.) bead, albeit thus far represented only by a single specimen (d'Errico et al., 2020; Fig. 16). Lithics in Layer 16–13 (67–54 ka, MIS 4) are dramatically different from those in Layers 19–17 (78–72 ka, late MIS 5) across the parameters of reduction technology, rock type preferences, and size. The Layer 16–13 lithics show a marked increase in the use of bipolar technology relative to Layers 19–17, in terms of the proportion of both cores (Fig. 8) and large flakes (Table 6). This phase of occupation also evidences the appearance of prismatic blade technology and an increase in blade production, as indicated by the proportion of blade scars on cores, the elongation of large flakes, and the proportion of parallel dorsal scar patterns (Fig. 12; SOM Figs. S8, S9, S13; Table 10).

The starkest contrast between Layers 16–13 and those below is the switch from limestone to quartz as the dominant material, and the concomitant reduction in artifact size (Fig. 16). This change in material types is abrupt, and the change in lithic size is statistically significant for overall debitage, quartz and chert debitage, complete flakes, and complete quartz and chert flakes (Fig. 6; Table 4). This indicates that it is not the material change per se that drives this change, but the shift to quartz and chert in combination with a preference for creating small flakes of those materials. Comparable dorsal scar densities on quartz and chert flakes longer than 25 mm from above and below this transition, as well as a weak relationship between flake size and scar density, suggest that this difference in size is not primarily due to reduction intensity.

The shift to quartz and chert and the reduction in size across the Layer 17–16 boundary, persist through the remainder of the sequence (Fig. 16). Quartz is the dominant material in Layers 16–5, with quartz and chert dominant in Layers 4–1 (Fig. 4). Debitage also remains relatively small from Layers 16–1 upwards. Particular artifact types, such as large flakes, Levallois flakes, or retouched flakes are all significantly smaller in length, width, thickness, platform width, and weight from Layer 16 upwards (SOM Fig. S12; Tables 7 and 12).

Layer 14, an ashy loam, has the highest density of lithics in the MIS4 part of the sequence (Layers 16–13: 67–54 ka) (Table 3). Distinct peaks in magnetic susceptibility parameters in this layer point to heavy anthropogenic alteration (Shipton et al., 2018). In comparison to the rest of the sequence, Layer 14 has a low proportion of cores (Fig. 7) and no retouched flakes whatsoever (Fig. 14). Over 90% of the lithics from this layer were made on the most local material, quartz (Fig. 4). We suggest that this reflects a pronounced place provisioning strategy (Kuhn, 1992) under conditions of low mobility foraging: clasts were transported to the site and much reduction took place on site, resulting in many flakes being recovered for each core. The prevalence of the bipolar reduction strategy in this phase (Table 6) also suggests low levels of technological investment, with little need for standardization in tools that were only intended for local immediate use (Kuhn, 1995). Layer 14 has a higher terrestrial mollusc diversity than either of the two layers immediately preceding or succeeding it (Shipton et al., 2018), suggesting a relatively humid environment. Increased precipitation may have provided more surface water in the vicinity of the cave in this period, thereby making localized foraging a viable strategy.

Layers 12 and 11 (54–48 ka, early MIS 3) have the highest density of lithics in the MIS 3 part of the sequence (Table 3). However, in contrast to Layer 14, they have a very high proportion of cores, a high proportion of retouched pieces, and more of the most distant material, chert, than any of the three layers immediately preceding and succeeding them (Figs. 4, 7, and 13). We suggest that this reflects a distinct person provisioning strategy (Kuhn, 1992), in which, under conditions of high mobility foraging, cores were curated, and much reduction took place off site, resulting in relatively few unretouched flakes being recovered for each core. Low proportions of cortical dorsal surfaces on large flakes (Table 9) also suggest high levels of core curation, while redirecting flakes indicate the deliberate prolonging of core use-lives (Table 6). Relatively high levels of retouch may also partly be attributed to the prolonging of use-life of some flakes. Many of the retouched pieces in Layers 12 and 11 are backed pieces (Fig. 16): standardized, predictable tool forms, that could be relied upon in longer distance foraging (Clarkson et al., 2018a). Levallois cores (Fig. 10) and high proportions of prepared platforms and Levallois flakes (Table 6) also indicate the use of formal reduction strategies to produce standardized products. Both retouch rates and lithic densities are high in Layers 12–11 (Table 3; Fig. 13), suggesting that, unlike much of the rest of the sequence, the site was used as a temporary camp in a person provisioning or residential mobility strategy during this period (Barton and Riel-Salvatore, 2014), but intensively so, perhaps as a seasonal aggregation site.

Several variables indicate that Layers 12 and 11 (54–48 ka, early MIS 3) were deposited when the climate was at its driest and the landscape around Panga ya Saidi at its most open: Layers 12 and 11 have the highest proportion of open-country suids and large bovids, the highest stable carbon and oxygen isotope values, the lowest proportion of woody phytoliths, and the lowest terrestrial mollusk diversity in the sequence (Roberts et al., 2020; Shipton et al., 2018). Compared to the interior, conditions at Panga ya Saidi remained relatively mesic (Roberts et al., 2020), but this part of the sequence represents a local peak in the openness of the environmental setting. Under these drier conditions, the occupants of Panga ya Saidi may have ranged over greater distances to access water sources, prey, and other resources. The Kilifi Creek would have been a river at this time and a key focus of the foraging landscape. Chert clasts available there and in eroding smaller streams in between possibly account for the increase in chert use at this time. It is widely accepted that backed artifacts in African archaeological contexts were associated with the use of compound tools and multistate weaponry such as the bow-and-arrow (Lombard, 2011; Lombard and Pargeter, 2008; Lombard and Phillipson, 2010; Villa et al., 2010; Wurz and Lombard, 2007). At Panga ya Saidi, the backed pieces from Layers 12 and 11 may have been used in such complex armatures to bring down the large bovids prevalent in this part of the sequence.

Layer 10 (48–40 ka, mid MIS 3) maintains many of the formal aspects of lithic technology seen in Layers 12 and 11, such as Levallois and a high proportion of prepared platforms (Fig. 11; Table 6). Backed artifacts are absent, however, and the proportion of cores is reduced. Carved osseous artifacts are present in the middle part of the sequence, Layers 10 to 7, where backing is absent (Fig. 16), perhaps partly representing a change in armature technology as one of the bone artifacts from Layer 9 has been interpreted as a broken arrow point (d'Errico et al., 2020).

Layer 9 (40–29 ka, late MIS 3) represents a marked shift back to a place provisioning strategy, with over 90% of lithics being quartz (Fig. 4) and very little retouch (Fig. 13). The scarcity of chert is noteworthy, because, with falling sea-level in late MIS 3, fluvial incision and exposure of chert nodules likely increased. A high proportion of cortical dorsal surfaces, low scar densities, and the absence of old platforms (redirecting flakes) on large flakes suggest low levels of reduction intensity (Tables 6 and 10). A high proportion of bipolar flakes and crushed platforms, low proportions of platform preparation, and a complete absence of Levallois technology indicate informal reduction strategies (Tables 6 and 9). Layer 10 has yielded two carved suid tusks, possibly awls, and an engraved ocher crayon;

while Layer 9 contained notched bones and the earliest ostrich eggshell bead thus far documented in the sequence (Fig. 16; d'Errico et al., 2020). These contrasting assemblages of organic and symbolic artifacts correlate with the lithic technological differences between the layers, suggesting a significant cultural transition at this point in the sequence, although there is also continuity in the presence of *Conus* sp. beads.

Layers 8 and 7 (29–20 ka, early MIS 2) contain two further examples of notched bones, as well as numerous ostrich eggshell beads which are found throughout the remaining upper part of the sequence (Fig. 16; d'Errico et al., 2020). These layers have the highest density of lithics in the sequence (Table 3) and represent a culmination of the place provisioning strategy in which the site was used as a long-term basecamp. Low proportions of cores and retouch (Figs. 7 and 13) indicate on site reduction, while low scar densities and high proportions of cortical dorsal surfaces indicate low levels of reduction intensity (Tables 6 and 10). Informal technology is manifest by the highest proportions of bipolar cores and flakes, and low proportions of prepared platforms on large flakes (Fig. 8; Tables 6 and 9). Flake elongation and the proportion of blade scars on cores rise in Layers 8–7, reflecting both bipolar blades and the reappearance of prismatic blade cores.

The ostrich eggshell beads are particularly noteworthy in relation to mobility as ostriches are not endemic to the Nyali Coast, there is no evidence of on-site bead manufacture, and the beads are of multiple distinct types (d’Errico et al., 2020). The proliferation of these beads in Layers 9-7 coincides with lithic technological as well as faunal signatures for reduced mobility, suggesting the beads were being acquired not through ranging but by exchange. Interregional connections appear to increase as local mobility decreases; perhaps as the result of a more densely inhabited regional landscape (Tryon and Faith, 2016).

Layers 6 and 5 (~14.5 ka, late MIS 2) document the reintroduction of backed artifacts, with the addition of new trapezoidal and triangular forms (Fig. 16). Rates of retouch begin to climb in these layers while artifact densities fall (Fig. 13; Table 3), suggesting a shift away from the place provisioning strategy to increasing residential mobility (Barton and Riel-Salvatore, 2014). Notably, marine subsistence resources are first imported in Layer 5 alongside high proportions of chert, the source for which occurs between Panga ya Saidi and the coast (Fig. 3).

In the final, Holocene layers (4-1) of the sequence, there are numerous backed artifacts (Fig. 16). The Holocene lithics see a marked person provisioning strategy with very high proportions of chert and retouch (Figs. 4 and 13), and, in the late Holocene Layers 3–1, a high proportion of cores (Fig. 7). High proportions of prepared platforms and low proportions of bipolar flakes and crushed platforms indicate more formal reduction (Tables 6 and 9). Environmental proxies indicate a return to warm, wet conditions at this time with increased values of magnetic susceptibility, lower stable isotope values (Fig. 16), high proportions of small bovids typical of closed habitats, and high proportions of woody phytoliths (Roberts et al., 2020; Shipton et al., 2018). Exploitation of marine mollusks for food becomes more intense in the Holocene layers, with the mobile occupants of the site likely exploiting the Kilifi Creek, which was flooded as a result of post-LGM sea level rise. With the exception of a single specimen in Layer 5, the Holocene sees the uptake of small manufactured marine disc beads, as well as several whole gastropod beads, further testifying to increasing coastal engagement (d'Errico et al., 2020). A reduction in lithic density (Table 3) and an increasing proportion of bats and rodents in the faunal remains (Roberts et al., 2020) suggest that people used the cave progressively less frequently in the late Holocene.

4.2 Overview of the Panga ya Saidi sequence

The Panga ya Saidi lithic sequence begins in late MIS 5 with lithic technology typical of the MSA, featuring Levallois, centripetal reduction, and large retouched flakes; it ends in the recent past with technology typical of the LSA, featuring prismatic blade production and backed artifacts. In between, there are a variety of technological phases, some characterized by formal Levallois technology and others characterized by informal bipolar technology. We argue that the variation between these technological phases is best explained by shifts from person to place provisioning and changes in foraging mobility, in response to water availability and the shifting ecological affordances of the landscape around the cave. Backed artifacts first appear early in MIS 3 (54–48 ka), but then disappear from the sequence for tens of thousands of years. Similarly, systematic blade production first occurs in the 67–54 ka occupation phase, but then disappears for tens of thousands of years.

The organic artifacts from Panga ya Saidi suggest a significant transition between Layers 10 and 9 (~40 ka) from local coastal material culture such as *Conus* sp. beads, to items found elsewhere in Africa such as ostrich eggshell beads, notched bones, and bone points (d'Errico et al., 2020). The lithic technology suggests that this shift coincides with a reduction in mobility at Panga ya Saidi, with increased contact with neighboring groups a possible explanation for this. In the Holocene, marine-focused symbolism again comes to the fore, reflecting a shift in the focus of subsistence activity to the newly flooded Kilifi Creek Lagoon.

In so far as data from one sequence allows us to assess demography through occupation intensity (Reynard and Henshilwood, 2018), the latter, as manifest through lithic density, reaches a nadir during the upper part of Layer 17 (~72 ka, MIS 5–4 transition). Magnetic susceptibility supports the inference of the lowest occupation intensity at this time, while this and other occupation intensity proxies, including sediment facies, relative abundance of putative human inputs in the sediment, the frequency of charcoal, and the ratio of probable prey species to cave resident bats, all suggest fluctuating but generally increasing occupation intensity from Layers 16–1 (Shipton et al., 2018).

The most significant change in the Panga ya Saidi lithic sequence is the shift from limestone to sharper quartz and chert as the dominant materials, and the reduction in size of those quartz and chert artifacts. Miniaturized lithics are first evident in Layer 16 where the earliest bead thus far recovered also comes from, suggesting wider behavioral changes, although larger sample sizes will be needed to test this (d'Errico et al., 2020). The transition occurs between Layer 17 dated to the end of MIS 5 (72 ka), and Layer 16, dated to MIS 4 (67 ka). There is broad continuity in ecotonal mesic environments between Layers 19–17 and 16–13, and indeed throughout the remainder of the sequence. Nevertheless, within this paradigm of a benign and stable environment, the upper part of Layer 17 and the transition into Layer 16 potentially seems to represent a time of climatic perturbation and low occupation intensity; as indicated by a coarsening of the sediment, a drop off in magnetic susceptibility, and the lowest density of lithic artifacts. It is possible that these conditions were the prompt for the initial innovation of miniaturization. From Layer 16 onwards the Panga ya Saidi sequence is characterized by small and siliceous lithics, as well as increasingly intensive occupation and more regular instances of organic technology and symbolism (d'Errico et al., 2020). We suggest that it is miniaturization rather than any particular reduction strategy or tool type, such as prismatic blade production or backed artifacts, that distinguishes the LSA from the MSA at Panga ya Saidi.

4.3 The Middle to Later Stone Age lithic transition in eastern Africa and beyond

We document the origin of LSA technologies at Panga ya Saidi in MIS 4, identifying the miniaturization of lithic technology as a key unidirectional change in a sequence of human behavior spanning MIS 5–1. Here, we explore how the trends in material use, artifact size, and typology observed at Panga ya Saidi compare to other early LSA sites.

Within eastern Africa, an early transition from the MSA to the LSA has been documented at several sites in the Rift Valley. The Mumba rockshelter (Tanzania; Fig. 1) sequence is dominated by quartz throughout its MSA and LSA layers. A shift to bipolar as the dominant mode of flaking and a reduction in artifact size occurred by at least 57 ka (Gliganic et al., 2012), which has been taken to signal the transition from MSA to LSA (Eren et al., 2013). At the Nasera rockshelter (Tanzania; Fig. 1), a reduction in the size of non-bipolar cores, end-scrapers and points across the MSA-LSA transition is recorded (Fig. 1; Tryon and Faith, 2016). At Olduvai Gorge (Tanzania; Fig. 1), the early LSA has also been suggested to date to at least 57 ka (Skinner et al., 2003), with the transition from the MSA characterized by a shift from basalt to finer-grained chert, quartz, and obsidian as the dominant materials, and a reduction in lithic size (Leakey et al., 1972). Further north in the Rift Valley, the site of Enkapune ya Muto (Kenya; Fig. 1) preserves one of the oldest and longest LSA sequences in eastern Africa (Ambrose, 1998). Here, the initial LSA industry, dated to early MIS 3, was made on obsidian. With respect to the nearby MIS 5 obsidian dominated MSA site of Marmonet Drift, the initial LSA at Enkapune ya Muto shows a significant reduction in artifact size (Slater, 2016).

Levallois technologies are prominently associated with MSA industries in eastern Africa, but also occur in a number of LSA assemblages. In the early MIS 3 levels at Panga ya Saidi, miniaturized Levallois cores and flakes are a prominent feature of the assemblage. At Lukenya Hill (Kenya; Fig. 1), there is a pre-LGM ‘micro-Levallois’ industry, also characterized by recurrent centripetal knapping, small Levallois flakes, and small non-Levallois cores (Tryon et al., 2015).

In the Horn of Africa, at Goda Buticha (Ethiopia; Fig. 1), smaller debitage size helps to distinguish a Holocene LSA assemblage from an MSA assemblage of MIS 3 age (Pleurdeau et al., 2014). Across the MSA-LSA transition at Midishi 2 (Somalia; Fig. 1) there is overall continuity in tool and core types, but a reduction in size in all classes of stone artifact (Brandt and Gresham, 1990). At Mochena Borago (Ethiopia; Fig. 1), backed artifacts occur alongside small obsidian flakes throughout a sequence that dates back as far as 53 ka (Brandt et al., 2017), and which could be regarded as the early LSA of the region.

MSA populations already exploited some of the highly siliceous material types that dominate LSA assemblages, indicating that change in material use alone is not a sufficient index with which to track the MSA-LSA transition. However, all sites in eastern Africa that are notable for early manifestations of LSA industries show evidence of a distinct reduction in artifact size. This supports the assertion that the key unidirectional change in artifact size and material at Panga ya Saidi is an important marker for the emergence of LSA industries.

Despite this common theme in changing artifact size across the earliest LSA industries of eastern Africa, technological and typological changes are typically cited as indicators of the LSA. Taken in isolation, no single technological or typological trait consistently distinguishes the MSA and LSA at Panga ya Saidi. However, when constellations of traits are compared across eastern African assemblages, Layers 19–17 are classified as MSA assemblages, while Layers 16 and above fall are classified as LSA assemblages (Grove and Blinkhorn, 2020). The co-occurrence of three traits in particular were found to be useful in discriminating the MSA and LSA at a regional level: bipolar, blades, and backing. We discuss each of these below.

At both Mumba and Nasera, the dominance of bipolar technologies has been highlighted as a key change in reduction behavior associated with the earliest LSA (Eren et al., 2013; Tryon and Faith, 2016). This shift parallels the proliferation of bipolar knapping in the MIS 4 layers at Panga ya Saidi. However, given that not every post-MIS 5 layer at Panga ya Saidi is dominated by it, we suggest that the shift to bipolar technology at Panga ya Saidi and elsewhere is driven by an underlying preference for small, sharp flakes: bipolar flaking is well suited to knapping the small clasts in which very fine-grained materials such as quartz and chert are often available (Hiscock, 2015; Pargeter and Eren, 2017).

The initial LSA at Enkapune ya Muto represents one of the earliest examples of prismatic blade production in eastern Africa (Ambrose, 1998). In a review of miniaturized industries across the world, Pargeter and Shea (2019) found that systematic blade production is a common but not universal feature, with blades providing the advantage of a relatively long, straight cutting edge on a small tool. In both India and Sri Lanka for example, miniaturization is a key feature of assemblages in the last 50 ka, but only in the former is there systematic blade production (Clarkson et al., 2018b; Clarkson et al., 2020; Lewis et al., 2014; Mishra et al., 2013; Perera, 2010; Petraglia et al., 2009; Wedage et al., 2019; Wedage et al., 2020). The evidence from Panga ya Saidi supports this close, but decoupled relationship, with systematic blade production an early yet intermittent feature of the miniaturized LSA sequence.

The early backed artifacts at Panga ya Saidi in Layers 12 and 11 date from ~50 ka. At Mumba, backed artifacts occur from around the same time (Diez-Martín et al., 2009; Gliganic et al., 2012); and at Enkapune ya Muto they occur from this time or earlier (Ambrose, 1998). Ethnographic evidence and archaeological cases of exceptional preservation suggest that backed artifacts were primarily components of compound complex projectiles, such as bow-and-arrows and harpoons (Clark, 1975; Larsson et al., 2017; Lombard and Phillipson, 2010; Rudner, 1979; Tomasso et al., 2018). At Panga ya Saidi, the early backed artifacts are associated with larger and more open country bovid taxa (Fig. 16), perhaps because of their use in hunting such prey. At Nasera rockshelter, backed artifacts become more common during the LGM when open country bovids such as *Damaliscus* replace closed-habitat species, suggested to reflect the utility of bow-and-arrow hunting from a greater distance in more open environments (Tryon and Faith, 2016).

Backed artifacts have been characterized as the functional equivalent of disposable razor blades, their standardized shape making them readily replaceable without the need for replacing the entire tool (Ambrose, 2010). Miniaturized lithics in general might be regarded as a broader class of disposable tool, intended for short-term use and replacement, rather than curation. Some support for this hypothesis comes from an experimental study which found that stone tool sharpness drops rapidly upon use (Key et al., 2018). Highly siliceous materials such as chert and quartz, have the advantage of being initially sharper, but do not hold their edges as well as coarser-grained rock (Key et al., 2020). For tasks that require particularly sharp edges, it may be better to use more siliceous rocks and make many small disposable edges, rather than fewer longer, more durable edges. Short use-lives of individual lithics may explain why levels of retouch on the working edge are significantly lower in the miniaturized LSA than in the MSA, both at Panga ya Saidi and at sites in the Rift Valley (Slater, 2016). At Panga ya Saidi (d'Errico et al., 2020) and elsewhere in eastern Africa (Langley et al., 2016), osseous carving was often done with multiple unretouched flakes, indicating one function of miniaturized lithics and providing a link with the carved osseous artifacts associated with the LSA.

Beyond eastern Africa, there is some suggestion that the MSA-LSA transition follows a similar pattern of miniaturization. In southern Africa, an early MSA-LSA transition has been documented at Border Cave (Villa et al., 2012). There, ~43 ka, there was a shift from relatively large lithics made through freehand percussion of microcrystalline rhyolite, to small flakes produced through bipolar knapping of quartz and chalcedony. An emphasis on bipolar reduction characterizes early LSA assemblages in general in southern Africa (Bousman and Brink, 2018). At Uhmlatuzana and Rose Cottage Cave, the initial LSA is distinguished from the MSA by the increased use of bipolar flaking of quartz clasts and a reduction in artifact size (McCall and Thomas, 2009). Likewise, MSA and LSA layers at Erb Tanks Rockshelter are distinguished by the contrast in lithic size (McCall et al., 2011).

In the Congo basin of central Africa, LSA assemblages are characterized by bipolar knapping of quartz (Mercader and Brooks, 2001; Van Noten, 1977). Farther west, Shum Laka Rockshelter in Cameroon, shows production of small quartz flakes from the last 30 ka until the middle Holocene (Cornelissen, 2003). LSA occupations further west are similarly dominated by the knapping of small quartz flakes (Chenorkian, 1983; MacDonald, 1997; Shaw and Daniels, 1984).

The Panga ya Saidi lithic sequence shares many features with other MSA-LSA eastern African sites. The emphasis on bipolar knapping in MIS 4 and MIS 2 also occurs at Mumba and Nasera; early blade production occurs at Enkapune ya Muto; and both Enkapune ya Muto and Mumba have backed artifacts from early MIS 3. Nevertheless, at Panga ya Saidi, none of these traits represent unidirectional changes; instead, they occur recurrently within the context of an overarching unidirectional shift to miniaturized lithics 72–67 ka.

Paleoclimate records from lakes on nearby Mount Kilimanjaro offer contradictory perspectives on the MIS 5–4 transition, with that from Lake Challa suggesting a moist climate throughout (Moernaut et al., 2010), while that from Lake Maundi points to a ~70 ka drought (Schüler et al., 2012). While a short-lived environmental perturbation may have prompted the initial switch to miniaturization at Panga ya Saidi, the subsequent innovations through MIS 4–1 are set against an environmental backdrop of a persistent tropical forest ecotone. Several African paleoenvironmental records indicate that the continent as a whole was characterized by greater climatic stability after 70 ka (Lamb et al., 2018), but these differ in directionality, with records from Kilimanjaro and Lake Malawi indicating more precipitation (Moernaut et al., 2010; Scholz et al., 2007; Schüler et al., 2012; Stone et al., 2011), while those from offshore west Africa, Lake Victoria, and the lower Nile indicate less precipitation (Beverly et al., 2017; Davies et al., 2015; Stager et al., 2011). Panga ya Saidi appears to conform to the latter pattern, with relatively drier environments during the Last Glacial Period, while its mesic coastal location seems to have buffered it from the extremes of aridity in MIS 2 (Shipton et al., 2018; Roberts et al., 2020).

Lithic miniaturization across the MSA-LSA transition is a feature not just of Panga ya Saidi, but also of MSA-LSA sequences across eastern Africa and other regions of the continent. We suggest that lithic miniaturization may be a key distinguishing feature of the LSA throughout Africa, representing a new mode of lithic use in which edge sharpness was prioritized over longevity. This disposable razor theory of the LSA (Ambrose, 2010), likely involved new functions for stone tools, as well as new multi-component ways of hafting.

5. Conclusions

The transition from the MSA to the LSA is one of the most significant changes in behavior in later human evolution. It has been suggested to represent a key genetic, cognitive, or demographic change that may have led to major human dispersals (Klein, 2002; Rito et al., 2019; Tryon and Faith, 2016). Recent reviews stress the variable nature of this transition across Africa (Will et al., 2019a) and even within eastern Africa (Tryon, 2019), and thus the need for contextualization. Panga ya Saidi, with a particularly long Late Pleistocene human occupation sequence directly associated with environmental proxies, provides an opportunity to address hypotheses of the MSA-LSA transition.

Stone artifact features that have been seen as important markers of the LSA elsewhere, including systematic blade production and backed microliths, are present at Panga ya Saidi under particular conditions of mobility and paleoenvironment; however, they are not universal features of the LSA record. An emphasis on bipolar flaking and a low percentage of retouch characterizes much of the sequence, but not the Holocene. The organic artifact sequence suggests an important transition with the introduction of ostrich eggshell beads, bone points, and notched bones ~40 ka, but these do not coincide with any lithic technological markers of the LSA (Fig. 16). The clearest unidirectional shift at Panga ya Saidi is to small, fine-grained flakes, evident from 67 ka.

In contrast to the limestone lithics in MIS 5, fine-grained quartz and chert dominate in all layers of the Panga ya Saidi sequence from MIS 4 onwards. Post-MIS 5 lithics from the site are smaller by all measures (mean debitage weight, the surface area of large chert and quartz flakes, and individual dimensions of Levallois and retouched flakes). Levels of scar density are comparable between the MSA industry of late MIS 5 age and later industries, suggesting that miniaturization was not primarily driven by higher reduction intensity. Across the Layer 17–16 transition, the reduction in size of debitage and complete flakes notably applies only to chert and quartz, not to limestone. This indicates that the derived shift to more siliceous materials was accompanied by a change in size preference for those materials in particular. Lower levels of retouch on the working edge in the Layer 16–1 lithics provide a further clue as to what may be driving this change: the prioritization of sharpness over edge durability. The widespread occurrence of miniaturization in the MSA-LSA transition elsewhere in eastern Africa and further afield, suggests that miniaturized lithics might be a key diagnostic feature of the LSA in general.

Panga ya Saidi is thus far the earliest documented site where a unilinear shift towards miniaturization persists well into the Holocene. The evidence from the site indicates novel behavior prior to miniaturization, as the MSA occupation occurs in an unusual low-altitude, humid, tropical forest setting. The end of MIS 5 saw the manifestation of broader climate change at the site, with sedimentary and magnetic susceptibility evidence for drier and cooler conditions, likely fashioning a more open, mosaic landscape in the vicinity of the cave. A possible corollary of environmental change during the MIS 5–4 transition may have been that water sources in the limestone terrain around Panga ya Saidi became scarcer and/or less dependable to human foragers (and their prey). Lithic density was extremely low at this time, perhaps indicating a population under stress. These conditions seem to have prompted the initial switch to miniaturization, with such lithics evident from MIS 4, alongside a new depositional regime recording increasingly intensive human occupation.

While changes at Panga ya Saidi across the MIS 5–4 transition parallel important changes at this time in southern Africa (Jacobs et al., 2008), there is no sense in which the changes in the two regions are homologous. Thus the innovation of miniaturization does not appear to have been introduced to eastern Africa via a hypothesized dispersal from the south (Rito et al., 2019). Nor is there any evidence for a common coastal adaptation between the regions (Will et al., 2019b), given the absence of marine subsistence until after the LGM at Panga ya Saidi (Shipton et al., 2018). The occupation of a unique environment for eastern Africa suggests ecological range expansion in the MIS5 MSA (Blinkhorn and Grove, 2018). To the extent that we can discern palaeodemography from the occupation intensity of a single site, the Panga ya Saidi record suggests that innovations such as backing may have taken place in the context of increased population density (Archer, 2021), with the hunting of larger prey a probable functional reason for the technology. However, the initial switch to miniaturization occurred when occupation intensity was very low, with a relatively short-lived climatic perturbation at the MIS 5–4 transition potentially spurring the innovation. The range of functions that miniaturized LSA toolkits were employed for is not yet clear. Sharpness seems to have been the paramount consideration—with new, single-cut and multiple component ways of using stone tools (Ambrose, 2010; Slater, 2016), perhaps explaining the dominance of miniaturization in the LSA at Panga ya Saidi and across Africa.

Acknowledgements

Funding was provided by the Sealinks project under a European Research Council (ERC) grant (no. 206148; awarded to N.B.), the McDonald Institute for Archaeological Research, University of Cambridge (awarded to C.S.), and the Max Planck Society. Permission to conduct the research was granted by the National Council for Research and Technology (NACOSTI) through affiliation with the National Museums of Kenya (NMK). We thank Gedion Musuko and family for permission to excavate at Panga ya Saidi. We are grateful for the support of the NMK and the British Institute in Eastern Africa. We thank Louise Green, Joyce Wathira, and James Munene for their assistance during data collection. Three reviewers and two associate editors provided detailed comments that were used to improve drafts of this paper.

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Figure captions

Figure 1. The location of Panga ya Saidi (PYS) and other sites mentioned in the text relative to present day ecological zones of Africa (Olson et al., 2001).

Figure 2. A) Location of the Panga ya Saidi excavation within the cave. The main excavation includes Trenches 1 and 3-8, while Trench 2 is situated in a different chamber. B) Panga ya Saidi Trench 4 west, north, and east sections at the end of excavation. Layer numbers are shown on the right section and Bayesian modeled ages are shown between the north and east sections. Rocks are shown in light gray and termite galleries in black.

Figure 3. Satellite image of Panga ya Saidi and surrounding region showing the nearest sources of the three main rock types used for knapping at the site, as well as the perennial

river that provides the nearest permanent fresh water source, and the Kilifi Creek lagoon that is the nearest (marginal) marine environment.

Figure 4. Distribution of lithic materials by layer at Panga ya Saidi. The small quantity of exotic materials are shown in purple. Note that limestone is dominant at the beginning of the sequence (Layers 17–19) but drops off significantly between Layers 17 and 16, with quartz dominating the middle of the sequence, and quartz and chert dominating the upper four layers.

Figure 5. Mean debitage weight in grams in the Panga ya Saidi sequence by layer. Note the drop between Layers 17 and 16 that is then consistently maintained through the rest of the sequence.

Figure 6. Violin plot of lithic debitage weight for Layers 18–15 at Panga ya Saidi. Note the reduction in weight between Layers 17 and 16.

Figure 7. Percentage of cores in the Panga ya Saidi sequence by layer. Note the peaks in Layers 16, 13–11, and 3–1.

Figure 8. Proportion of core types by layer in Trenches 1, 3, and 4 in the Panga ya Saidi sequence. Sample sizes are shown at the bottom of each column.

Figure 9. Examples of bipolar cores from Panga ya Saidi: A) quartz core from Layer 9; B) quartz core from Layer 4; C) chert core from Layer 5; D) limestone core from Layer 9. Scale bar 1 cm.

Figure 10. Examples of chert Levallois cores from Panga ya Saidi: A) recurrent Levallois bidirectional core from Layer 3; B) recurrent unidirectional Levallois core from Layer 5; C) Levallois core from Layer 19; D, E) recurrent centripetal Levallois cores from Layer 11. Scale bar 1 cm.

Figure 11. A selection of Levallois flakes from Panga ya Saidi: A) chert Levallois blade from Layer 4; B) chert Levallois flake from Layer 5; C, D, F) chert Levallois flakes from Layer 10; E) large limestone Levallois flake from Layer 19. Scale bars 1 cm.

Figure 12. Violin plot of large flake elongation for Layers 12 to 19 of Panga ya Saidi Trench 4. The reference line is at 2.2.

Figure 13. Proportion of Panga ya Saidi lithics that are retouched pieces in each layer.

Figure 14. Retouched Levallois flakes from Panga ya Saidi: A) retouched along much of both margins on the dorsal surface, as well as intermittently on the ventral surface, from Layer 19; B) marginally retouched blade from Layer 12; C) marginally retouched on the proximal lateral edges, Layer 17. Scale bar 1 cm.

Figure 15. Backed and ventrally retouched artifacts from Panga ya Saidi Layers 12–1: A) triangle from Layer 3; B, C) crescents from Layer 4; D) crescent from Layer 6; E) triangle from Layer 5; F, G) crescents from Layer 12; H, I) crescents from Layer 11; J) broken ventrally retouched piece from Layer 11. Scale bar 1 cm.

Figure 16. Selected environmental and lithic variables by layer(s) through the Panga ya Saidi sequence. From left to right: magnetic susceptibility (mean N χlf); the proportion of browsers and grazers in the macromammal remains, excluding hyrax (NISP); mammal teeth stable isotope values (δ13C); mean lithic debitage weight (g); the proportion of lithic material types; key artifacts types (from top to bottom: a Levallois point; a bipolar core; a backed crescent; a notched bone, broken bone point, and tusk awl; backed triangles); shell bead types (*Conus, Volvarina, Struthio,* and ground marine shell).