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Late Acheulean occupations at Montagu Cave and the pattern of Middle Pleistocene behavioral change in Western Cape, southern Africa

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ABSTRACT

Patterns of so-called modern human behavior are increasingly well documented in an abundance of Middle Stone Age archaeological sites across southern Africa. Contextualized archives directly preceding the southern African Middle Stone Age, however, remain scarce. Current understanding of the terminal Acheulean in southern Africa derives from a small number of localities that are predominantly in the central and northern interior. Many of these localities are surface and deflated contexts, others were excavated prior to the availability of modern field documentation techniques, and yet other relevant assemblages contain low numbers of characteristic artifacts relative to volume of excavated deposit. The site of Montagu Cave, situated in the diverse ecosystem of the Cape Floral Region, South Africa, contains the rare combination of archaeologically rich, laminated and deeply stratified Acheulean layers followed by a younger Middle Stone Age occupation. Yet little is known about the site owing largely to a lack of contextual information associated with the early excavations. Here we present renewed excavation of Levels 21–22 at Montagu Cave, located in the basal Acheulean sequence, including new data on site formation and ecological context, geochronology, and technological variability. We document intensive occupation of the cave by Acheulean tool-producing hominins, likely at the onset of interglacial conditions in MIS 7. New excavations at Montagu Cave suggest that, while Middle Stone Age technologies were practiced by 300 ka in several other regions of Africa, the classic Acheulean persisted later in the Fynbos Biome of the southwestern Cape. We discuss the implications of this regionalized persistence for the biogeography of African later Middle Pleistocene hominin populations, for the ecological drivers of their technological systems, and for the pattern and pace of behavioral change just prior to the proliferation of the southern African later Middle Stone Age.

1. Introduction

While our understanding of variability in hominin behavior in the African Early Stone Age (ESA) has increased substantially over the last two decades, much of this information derives from the eastern African rift system where well-constrained geochronologies

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and tightly associated material remains yield detailed data on hominin adaptive responses to evolving landscapes through the Plio-Pleistocene (Kingston, 2007; Archer et al., 2014; de la Torre et al., 2014; Presnyakova et al., 2018; Braun et al., 2019; Reeves et al., 2021). Comparative contexts in southern Africa are largely confined to non-occupational cave deposits (Herries and Shaw, 2011; Granger et al., 2015; Kramers and Dirks, 2017; Pickering et al., 2019), whereas well-contextualized cave occupations are largely confined to the last ~200 kyr (Jacobs et al., 2008; Marean, 2010; Tribolo et al., 2013; Wilkins et al., 2021).

The paucity of southern African ESA sites with well-constrained evidence for hominin occupation is particularly evident in the period between ~1.8 Ma and 0.3 ka, which is conventionally associated with the Acheulean techno-complex (Herries, 2011; Braun et al., 2016; Duke et al., 2021). The Acheulean is traditionally recognized through the presence of a characteristic tool type known as Large Cutting Tools (LCTs). Early assemblages with LCTs are thought to represent the onset and proliferation of several behavioral innovations, including the expansion of foraging ranges and raw material procurement, increased depth of planning, expanded consumption of animal tissues, and perhaps also increased hominin brain size (Féblot-Augustins, 1993; Ruff and Walker, 1993; Aiello and Wheeler, 1995; Potts, 1998; Braun and Harris, 2003; Sampson, 2006; de la Torre et al., 2014). Despite the precocious nature of LCT technologies when viewed against preceding African ESA industries, in the few Acheulean contexts potentially associated with hominin remains, LCTs have not been associated with the activities of anatomically modern hominins (Clark et al., 2003; Klein et al., 2007; Potts et al., 2018). Rather, in situ early *Homo sapiens* remains have been found exclusively in association with Middle Stone Age (MSA) assemblages.

Sites in the later Middle Pleistocene period—more recently referred to as the later 'Chibanian'—~400–200 ka (the later MP) are scarce in the southern and western Cape regions of South Africa relative to succeeding Stone Age occupations (Klein et al., 1999; Feathers, 2002; Herries, 2011, 2011; Braun et al., 2013; Caruana and Herries, 2021; Herries et al., 2022). The lack of archaeological evidence in this period is unfortunate as scientists widely assume that terminal Acheulean hominins made behavioral advances that forecast the later transition to behavioral modernity (Marean and Assefa, 2005). In fact, southern African occupations in MIS 9–6 are rare and patchily distributed regardless of industrial affiliation (Will et al., 2019), with understanding of hominin behavior in this period substantially reliant on the central interior localities of Kathu Pan and Wonderwerk cave (Fig. 1). Importantly, biostratigraphic estimates for the site of Duinefontein 2, located ~180 km west of Montagu Cave (MC) on the western Cape coast, are inferred to be ~300–250 ka, and the associated lithic assemblage is considered by some specialists to be potentially transitional between the ESA and MSA (Cruz-Uribe et al., 2003; Kuman et al., 2020). The scarcity of LCTs at Duinfontein 2 is, however, the very basis for the possible transitional attribution and, while the general presence of LCTs at this site is well established, the assemblage has never been published in detail. Additionally, classic Acheulean LCT assemblages have been recovered from well-contextualized layers at the site of Amanzi Springs dating—in different layers and locations—to ~534–390 ka (Caruana et al., 2023). Yet, despite a small number of recently well-excavated localities, the archaeological record immediately preceding the emergence of the southern African MSA remains poorly resolved in terms of geochronology and regional variability in hominin behavior (Chazan et al., 2008; Porat et al., 2010; Key et al., 2021; Chazan, 2022), in some respects echoing the temporal and spatial uncertainties of the African hominin record associated with this period (McBrearty and Brooks, 2000; Galway-Witham et al., 2019; Roksandic et al., 2021).

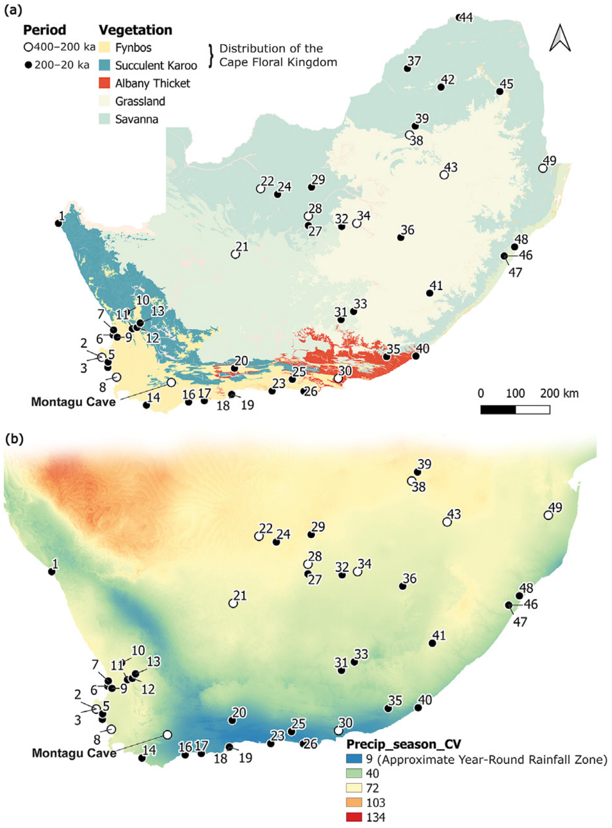

Figure 1. Pleistocene sites of southern Africa classified by geochronological occupation period plotted onto (a) vegetation biomes of southern Africa (Mucina and Rutherford, 2006) and (b) a raster of coefficient of variation (CV) in seasonal precipitation ('Precip_season_CV'; Hijmans et al., 2005), illustrating an exceedingly low CV between received summer and winter rainfall for the region of Montagu Cave indicative of the modern year-round rainfall. (1) Boegoeberg 1, (2) Sea Harvest, (3) Hoedjiespunt, (4) Ysterfontein, (5) Geelbek, (6) Elands Bay Cave, (7) Simons Cave, (8) Duinefontein 2, (9) Diepkloof Rockshelter, (10) Varsche Rivier 3, (11) Klein Kliphuis, (12) Hollow Rock Shelter, (13) Putslaagte 1, (14) Die Kelders, 16) Klipdrift Shelter, (17) Blombos Cave, (18) Pinnacle Point 13b, (19) Pinnacle Point 5–6, (20) Boomplaas, (21) Bundu Farm, (22) Kathu Pan 1, (23) Nelson Bay Cave, (24) Wonderwerk, (25) Paardeberg, (26) Klasies River Mouth, (27) Rooidam, (28) Canteen Koppie, (29) Witkrans, (30) Amanzi springs, (31) Highlands, (32) Erfkroon, (33) Hofmeyr, (34) Florisbad, (35) Blind River, (36) Rose Cottage Cave, (37) Olieboompoort, (38) Lincoln Cave, (39) Cave James, (40) Nahoon East London, (41) Strathalan Cave B, (42) Wonderkrater, (43) Cornelia, (44) Keratic Koppie, (45) Bushman Rock Shelter, (46) Umhlatuzana, (47) Shongweni, (48) Sibudu Cave, and (49) Border Cave. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Archaeologists have frequently associated later MP occupations of the interior regions of southern Africa—and occasionally also of the eastern African rift system—with the so-called Fauresmith industry (Tryon and McBrearty, 2002, 2006; Kuman et al., 2020). This term has been used variably to label assemblages in the terminal Acheulean, the earliest MSA, but more frequently to describe a mosaic industry with both ESA and MSA elements containing small LCTs (<12 cm in average length) that are relatively less numerous at the assemblage level than in the earlier Acheulean, large blades, rare prepared core flake production, and marginally trimmed convergent points (Goodwin and Van Riet Lowe, 1929; Mitchell, 2002; Porat et al., 2010; Kuman et al., 2020). What descriptions of transitional industries such as the Fauresmith have in common is the expectation of an archaeologically visible, gradual assembling of characteristic MSA technologies through the African later Middle Pleistocene, such as blades and points, and a concurrent loss of elements assumed to be relatively more reflective of archaic hominin behavior, such as LCTs. Within this trajectory of gradual innovative gain and concurrent loss of apparently maladaptive technologies, one might expect transitional industries with mosaics of Acheulean and MSA elements such as the Fauresmith (or the equivalents in equatorial African settings).

Interestingly, descriptions of the composition of the Fauresmith—as is also the case with several other southern African Stone Age entities—have tended to vary between researchers (Underhill, 2011; Wilkins, 2020) and the regional extent, geological determinants and chronology of the industry are still ambiguous (Humphreys, 1970). Similar challenges of compositional and geochronological consistency are shared by other supposedly ESA to MSA transitional industries such as the Sangoan and Lupemban. Recently, however, scientists have considered the label 'Fauresmith' important in describing assemblages that document the gradual technological refinement and overall decline of Acheulean technologies in the later MP of southern Africa, in favor of lighter and more diverse MSA toolkits (Wilkins and Chazan, 2012; Chazan, 2015; Kuman et al., 2020). It is widely assumed that these lighter MSA toolkits afforded hominins—argued by most scientists to be *H. sapiens*—key selective benefits over their Acheulean predecessors (Potts et al., 2018) and that, in the southwestern Cape, the ecological context of the Cape Floral Region (CFR) was one driver in the evolution and proliferation of later MSA technological behaviors (Marean, 2010). It is now clear that these lighter MSA toolkits were established to varying degrees in several regions of Africa by 500–300 ka (Wilkins and Chazan, 2012; Wilkins et al., 2012; Wilkins, 2013; Richter et al., 2017; Brooks et al., 2018); however, little is known about the tempo and process of behavioral evolution in contexts just preceding the onset of the MSA outside of eastern Africa. One reason for this gap in the southern African record is that the temporal and spatial extents of the Acheulean, including how these parameters vary relative to the local MSA, remain poorly documented.

Southern Africa has a relatively large number of MSA cave sequences dating to the last ~150 kyr, yet integrating this record with the local Acheulean has been challenging due to a paucity of well-contextualized and continuous cave sequences (Deacon, 1998). This is unfortunate as the end of the Acheulean, and by implication the origins of the local MSA, may be key to exploring the emergence of behaviorally modern humans (Hublin et al., 2017; Richter et al., 2017; Potts et al., 2018). Montagu Cave, located in the mountainous interior between the south and west coasts of South Africa, is well positioned to contribute relevant data to this issue (Fig. 1). The site contains multiple, well-stratified, dense concentrations of artifacts associated with ochre and plant remains such as phytoliths as well as fruit and seed casings, reflecting some of the latest Acheulean occupations of South Africa's southwestern Cape. The CFR within which MC is located has been key in our understanding of the environments in which southern African modern humans evolved.

Here we describe renewed excavations at MC, focusing on stratigraphy and site formation processes, technological variability emphasizing LCT production, geochronology of the lower layers, and ecological context of the Acheulean occupations. The recovery of in situ assemblages from MC documents Acheulean Middle Pleistocene hominin occupation in the CFR during MIS 7, reflecting the adaptations of hominins in the period directly preceding the first documented appearance and proliferation of modern humans in the southwestern Cape.

1.1. Montagu Cave and regional overview

Montagu Cave is a large cave formed within intensely folded sandstone formations of the Table Mountain Group, located approximately 160 km northeast of Cape Town, South Africa, on the flank of a southwest-oriented kloof (a steep-sided, vegetated, small valley) in the Langeberg mountain range of the Cape Fold Belt (Fig. 2a). The site is located close to the boundary of the modern year-round and winter rainfall zones (Fig. 1b) and, in accordance with aggregate regional paleo-vegetation archives, potentially experienced similar precipitation patterns for much of the last 300 kyr (Hijmans et al., 2005; Chase and Meadows, 2007; Dupont et al., 2021; Braun et al., 2023). Extremely fine-grained, primary sources of quartzite as well as perennial water and associated flora and fauna are available within 300 m of the cave today (Fig. 2a), suggesting minimal risk in the accessing of shelter, food, fuel, water, and high-quality stone, and that these resources may also have been available to hominins at a single location on the landscape for long periods of time in the past.

As previously mentioned, MC is located in the CFR, which has been relatively stable since the Late Miocene (Linder, 2003). This region has exceptionally high levels of biodiversity, with rich flora consisting of many endemics, and also contains a rich and diverse archaeological record pertaining to the last climate cycle (last ~150 kyr; Dupont et al., 2011). The history of hominin adaptation in the CFR continues to yield important insights onto our understanding of hominin behavioral variability and evolution (Marean, 2010; Braun et al., 2021) and has been crucial in documenting some key contexts in which southern African modern humans evolved (Parkington, 2001, 2010; Texier et al., 2010). Archaeological and natural terrestrial archives implicating hominin paleoecology in this biome, however, are scarce prior to the Last Interglacial (Rossouw et al., 2009; Dupont et al., 2021; Braun et al., 2023). Montagu Cave is the only documented site in the West Montane part of the year-round rainfall zone. This part of the year-round rainfall zone is the richest subregion of the CFR (Cowling and Lombard, 2002) and is nested among a mosaic of Fynbos and Mesic Renosterveld vegetation that contains abundant endemic geophytes that could have been viable food sources for hominins (Vlok et al., 2005; Mucina and Rutherford, 2006).

Oxygen and carbon isotope records drawn from a single speleothem located ~18 km west of MC documented climatic/biome stability across portions of the Middle Pleistocene period that MC was likely occupied, which was interpreted to underpin low rates of ecological change and correspondingly high present-day floral diversity in the immediate region (Braun et al., 2023). Broader inferences from Braun et al. (2023) would benefit from an increased sample of local paleoclimate records. That said, the implications of a relatively lower risk ecological context wherein resource availability may have been predictable over long periods of time suggests that MC may be well positioned to contribute to our understanding of the role of environmental variance in hominin adaptation (Potts, 1994, 1998), why specific behavioral strategies emerged or were retained in response to the effects of stable ecological parameters (Oswalt, 1976; Torrence, 1983; Collard et al., 2011), and the emergent stone artifact technologies resulting from this interplay (Braun et al., 2021; Iovita et al., 2021). Considering the proximity of MC to several well-dated MSA sites in the winter rainfall and year-round rainfall zones, aspects of the geochronology from MC in correspondence with contextual records of climatic variability may also contribute to our understanding of the pattern and pace of Middle Pleistocene behavioral evolution in the southwestern Cape (McBrearty and Brooks, 2000; Marean and Assefa, 2005).

1.2. Previous excavations at Montagu Cave

The history of research at MC was initiated with the 1919 excavations by Houghten and Barnard, who were from the institution known then as the Cape Town Museum (Goodwin, 1929; Goodwin

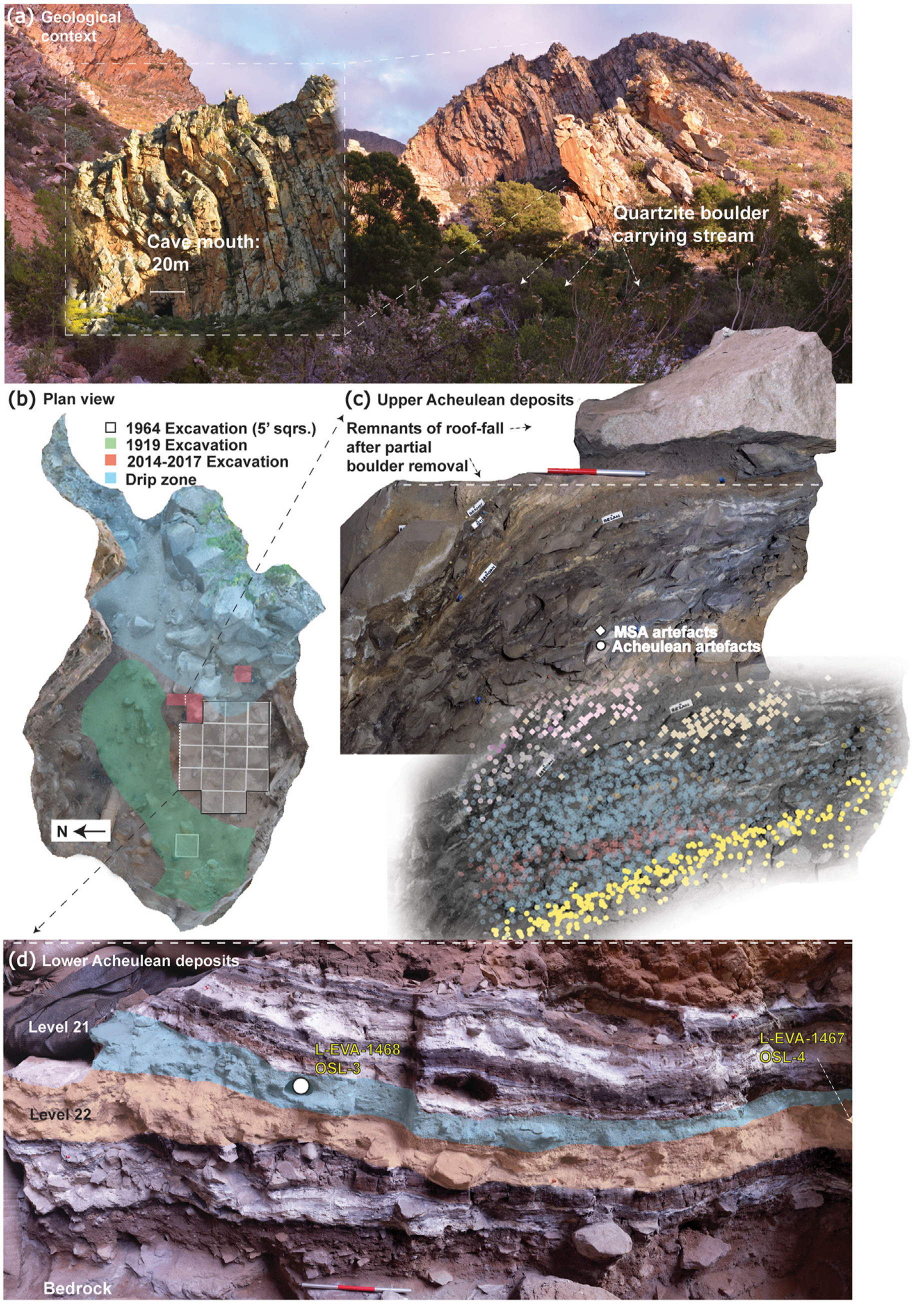

Figure 2. a) Southwest oriented view of the cave mouth with the river carrying quartzites below the site. (b) Structure-from-motion model showing the plan view of the frontal section of the shelter including previous excavation layouts. (c) Excavation of the upper Acheulean deposits with total station points of individual specimens of cultural material plotted. (d) Part of the lower Acheulean section where luminescence dating samples were extracted.

and Van Riet Lowe, 1929). More than 75% of the original archaeological deposits were apparently removed in this first excavation with unsystematic techniques (Keller, 1973), though reconstruction of the lateral extent of the 1919 excavation suggests this percentage is likely an overestimate (Fig. 2b). Keller's 1964–1965 excavations that followed were far more meticulous and, through manual bivariate piece-plotting (measuring X and Y), aimed to document stratified lateral distributions of stone artifacts in a portion of the remaining deposits, inferred then to be hominin living surfaces/floors (Keller, 1966, 1973). Although Keller's excavation focused on a smaller area of deposit in the cave than the 1919 campaign, his group recovered dense stone artifact assemblages from stratified contexts (n = ~275,000 excavated lithics, although components were transported to foreign institutions and never returned to South Africa), and also left a portion of unexcavated deposit pertaining largely to the Acheulean sequence. Under the Ph.D. supervision of Prof. J.D. Clark, Keller's interest in MC was aligned with the spatial focus of African Acheulean research around that time (Clark, 1954, 1964; Isaac and Isaac, 1977) and aimed to document the organizational use of the shelter by hominins through exploring lateral artifact densities, focusing less on the taphonomic contexts of the assemblages recovered and their technological implications.

The sheer size of the Acheulean sequence at MC, both in terms of artifact density and original sediment volume, is a significant feature of the site, and is certainly unusual if not unique among known Acheulean sites in southern Africa. In short, two lengthy

Acheulean sequences, with much the same technologies represented in multiple layers, are separated from one another by an archaeological hiatus. Above the second Acheulean sequence is an unconformity represented by roof collapse. The MSA and Later Stone Age (LSA) sequences follow this unconformity. The following description of the excavated sequence at MC draws on published terminology (Keller, 1966) relative to our on-site observations of remaining sections. Notably, here, the term ‘Layer’ refers to a sediment body with multiple internal stratigraphic entities that vary in color, compaction, and composition (essentially stratigraphic aggregates corresponding to a particular archaeological package of assemblages). Keller's excavations documented a sequence initiating with a lower Acheulean unit labeled by him as Layer 5, which started accumulating on the original bedrock of the cave. Layer 5 comprised multiple alternating black, white, and red organic-rich sand, silt, and clay lenses that dip toward the southeast (the cave mouth) and thicken in a westerly direction from the dripline toward the back of the cave, to a thickness of ~2.5 m. The Layer 5 deposits closer to the mouth (the east) have been post-depositionally deformed due to diagenesis and consequent loss of volume. Layer 4 overlies Layer 5 and is comprised of a thick homogeneous and archaeologically sterile ferruginous sand (>1 m thick in certain parts of the site). Following this sterile unit (Layer 4) was another shorter Acheulean archaeological sequence comprising black, white, and red laminated bands with sedimentological composition, compaction, and color variability similar to those of the stratigraphy of Layer 5, indicating a similar formational process. This upper Acheulean sequence was labeled by Keller as Layer 3 and, like Layer 5, dips towards the overlying boulders at the cave mouth. Both Acheulean units (Layers 5 and 3) contained dense, largely flat-bedded, classic Acheulean artifact assemblages (>550 LCTs were recovered from in situ stratigraphic contexts), which correlated with our observations and spatial data documenting these layers recorded in 2014–2017 (Fig. 3). Both Acheulean units, according to Keller, also had structured variability in the vertical density of accumulated anthropogenic materials, meaning concentrated lateral extents of artifacts interpreted as living floors, interspersed with relatively decreased more randomly distributed finds.

Directly overlying the upper Acheulean was Layer 2, which broadly contained MSA assemblages that extended in the vicinity of the dripline and sediment trap at the mouth of the shelter. No sedimentary hiatus was documented by the previous excavators between Layers 3 and 2; however, our work at the site documented a significant roof-fall event extended toward the dripline, between the accumulation of the latest Acheulean and youngest MSA in the cave (Fig. 2c). Due largely to substantial numbers of backed artifacts (so-called segments and trapezes) throughout the MSA levels, Keller attributed all of the MSA to the ‘Howiesons Poort’ industry (Volman, 1981); however, he also suggested in his dissertation that there were some affinities of the lower MSA at MC with the now obsolete quartzite-rich ‘Mossel Bay’ industry (Keller, 1966), which shares a small number of technological features with earlier MIS 5 assemblages from the sites of Elands Bay Cave, Diepkloof Rockshelter, and Klasies River Mouth (Porraz et al., 2013). Layer 1 was the relatively thin uppermost unit documented by Keller and contained LSA lithics. The LSA deposits were closer to the dripline and today are completely removed from the site. Surprisingly, during the removal of backfill from previous excavations (which contained substantial quantities of ex situ lithics) and during our own excavation, our team did not identify any unequivocal LSA artifacts. The lower LSA at MC was attributed by Keller to the ‘Robberg’ industry due to the frequency of bladelets, micolithic scrapers, and the prevalence of characteristic bullet-shaped bladelet cores (Porraz et al., 2016; Low and Mackay, 2018; Arthur, 2022), and the upper LSA to the Wilton (Keller, 1973; Mitchell, 2002). The raw material spectrum in Keller's named archaeological units were all dominated by local high-quality quartzites; however, the frequencies of silcretes and cherts were relatively higher in the MSA and LSA. Carbon 14 charcoal samples from the MSA levels, processed soon after the 1964–1965 excavations, yielded ages ranging from ~23.2 to 45.9 ka (Keller, 1973), which today cannot be considered reliable, given recent well-established yet contested luminescence chronologies published for the later MSA of the southwestern Cape (Jacobs et al., 2008; Tribolo et al., 2013). The Acheulean stratigraphic layers at MC were not previously dated. Our excavations documented abundant remaining in situ deposits of Keller's Layers 3–5, as well as pockets of ephemeral MSA deposits in less optimal taphonomic contexts, in amongst the boulders comprising the sediment trap.

Apart from recent fieldwork at Amanzi Springs in the Albany Thicket Biome, and research at older, largely deflated, open air sites ~180 km to the west of MC (Cruz-Uribe et al., 2003; Dietl et al., 2005; Klein et al., 2007; Archer and Braun, 2010; Kandel and Conard, 2012, 2012; Herries et al., 2022; Caruana et al., 2023), there are few contexts to explore how Acheulean hominins survived in the unique environments of the southwestern cape, and how their adaptations contrast with the much larger corpus of data on behaviorally modern hominins associated with the MSA of this region. It has been widely argued that MSA technologies offered later Middle Pleistocene hominins selective benefits relative to Acheulean technologies, particularly in the acquisition of resources in rapidly changing and unpredictable eastern African environments (Brooks et al., 2018; Potts et al., 2018). The inverse prediction is that certain Acheulean technologies may have actually enhanced extractive foraging abilities and/or optimized energy expenditure in low-risk contexts where resource availability was predictable for substantial periods of time, and group mobility was correspondingly low. This possibility perhaps warrants consideration in contexts where classic Acheulean technologies were practiced by hominins unexpectedly late, such as in the southwestern Cape, and where long-term Middle Pleistocene climatic/biome stability appears to be reasonably well established (Dupont et al., 2021; Braun et al., 2023).

1.3. Current research at Montagu Cave

A renewed field campaign at MC between 2014 and 2017 sought to recover a relatively small archaeological sample with modern excavation and digital recording techniques, to better contextualize the older systematically excavated collections and to generate detailed data on hominin occupation of the southwestern Cape during the later Middle Pleistocene. Prior to commencement of fieldwork, using a combination of historical photographs and modern three-dimensional (3D) reconstructions of the remaining deposits in the cave, we established that substantial deposits from the Acheulean horizons were still present near the mouth of the cave, sealed below a boulder collapse (falling of the roof overlying the cave mouth) that occurred between the Acheulean and MSA occupations of the site.

Here, we present the first results from the excavation, geoarchaeology, site formation, paleo-vegetation, as well as geochronology of these lower Acheulean deposits, focusing on the levels we were able to date: 21 and 22, which are identified here using Keller's (1966) IDs as the luminescence samples derive from the freshly exposed 1964 sections, which we subsequently excavated in several locations. The excavated levels and time period represented at MC proved challenging to date with available luminescence techniques. The current paper therefore focuses on occupations in the two stratigraphic levels from the Acheulean sequence, which

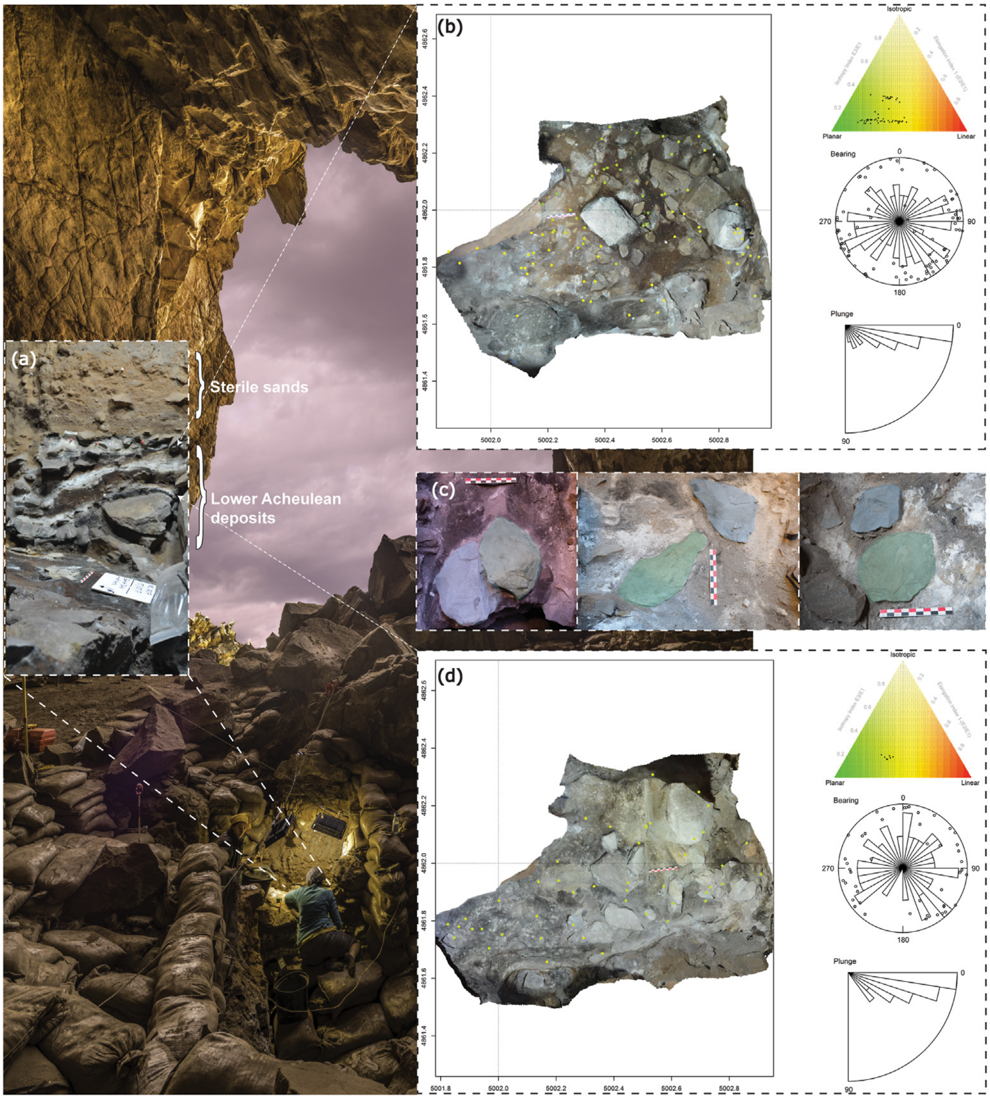

Figure 3. Recent small-scale excavation of dated lower Acheulean layers. (a) General excavation of lower Acheulean deposits during the 2017 field season. (b, d) Structure-from-motion models from within the two dated layers within the lower Acheulean sequence. Exposed two-shot finds (specimens with elongation axis >2.5 cm) are plotted with a published spatial analysis protocol; McPherron, 2018). The data are plotted relative to three simulated scenarios: isotropy, linearity, and planar (McPherron, 2018). Isotropy here refers to a scenario where artifacts have no systematic patterning with regard to their orientation; they are essentially randomly oriented in all directions. A linear assemblage means that elongated clasts have been preferentially oriented in the same direction by some process (water flowing through a deposit, for example). Planar means that artifacts are oriented in all directions but in a single plane or on a single surface, which is the expectation for the patterning of an assemblage which is close to resembling the positions in which artifacts were originally discarded. The relative colors of each point indicate the nature of individual artifact orientations relative to these extremes, in both cases showing a relatively preferable association with the planar extreme. The color key can be read from the Benn diagram on the top right. (c) Six complete Large Cutting Tools exposed in situ, in the dated layers in the lower Acheulean sequence in 2017 (scale is 10 cm). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

were dateable with luminescence techniques, to explore links between site formation and behavioral data. As the dated levels occur toward the base of the stratigraphic sequence (Fig. 4) and site formation suggests a probable rapid accumulation of Acheulean deposits, it may be reasonable to propose that the acquired ages provide a reflective age estimate for the Acheulean occupation of MC in general.

2. Materials and methods

2.1. Excavation methodology

We set up an excavation grid in June of 2014, aligning the horizontal angle with the East-facing orientation indicated by the ephemeral remains of the northern section from the 1964 excavation. We proceeded to excavate across 2 m^2, targeting MSA deposits in a trench laterally dislocated from the Acheulean deposits (Fig. 2b). Excavation followed modern digital standards of recording. The provenience of finds (e.g., artifacts, charcoal, and ochre) was documented with piece-plotted data. Remains larger than 2.5 cm were recorded in 3D using a total station. Plotted finds were allocated unique identification numbers associated with their spatial information as well as with other contextual and descriptive information recorded by a handheld computer linked to a total station. The amount of excavated sediment per stratigraphic subdivision (estimated by number of buckets, each with a standardized volume) was recorded, and the sediment was dry-sieved through both a 3-mm and a 1-mm mesh to obtain smaller materials such as

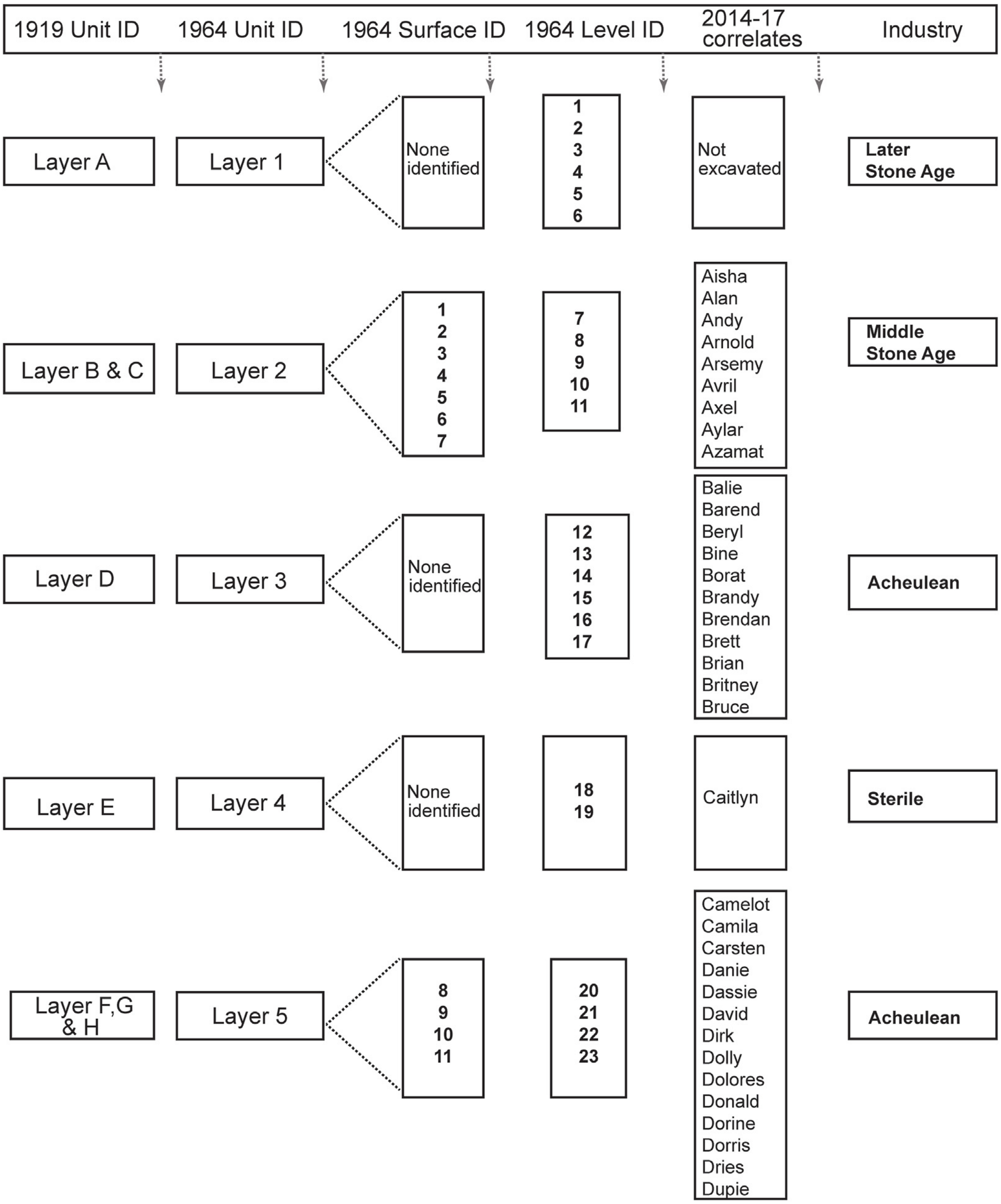

Figure 4. Correlations between stratigraphic entities documented in different excavations of Montagu Cave.

lithic debris and botanical remains (fruit and seed casings), which cannot be recovered without fine-sieving. All charcoal samples larger than 1 cm were measured in situ. Deposits were dug stratigraphically in accordance with the dip and strike of the encompassing body of sediment, and individual bucket volumes of sediment were recorded in X, Y, and Z with the total station. The surfaces and bases of all stratigraphic levels were mapped with a total station as well as photographed, and 3D structure-from-motion models were constructed for select lateral artifact distributions in each level identified. The deposits were systematically sampled for micromorphological analysis to investigate their formational microenvironments and history of deposition.

2.2. *Site formation and micromorphological observations*

Several high-resolution techniques are used to address aspects of site formation processes at MC, including soil micromorphology, Fourier transform infrared spectroscopy (FTIR), and microFTIR. The goal of this ongoing analysis is to reconstruct the origin of the sediments, to identify their depositional mechanisms as well as potential postdepositional processes. These aspects coordinate with other data collection initiatives and enable greater understanding of the degree of integrity present in the archaeological lithic assemblages that were excavated in previous campaigns, as well as in the current one. While in-depth studies of the processes that lead to the formation and degree of preservation of the deposits at MC are still underway, here we focus on sedimentological and micromorphological data available for levels 21 and 22. We particularly focus on micromorphological samples taken in close proximity to the optically stimulated luminescence (OSL) samples that provided date estimates for these two levels. Specifically, sample MC 107 in the northern section is associated with OSL 3 (L-EVA1468), and sample MC 103 in the eastern section is associated with sample OSL 4 (L-EVA1467; Fig. 5).

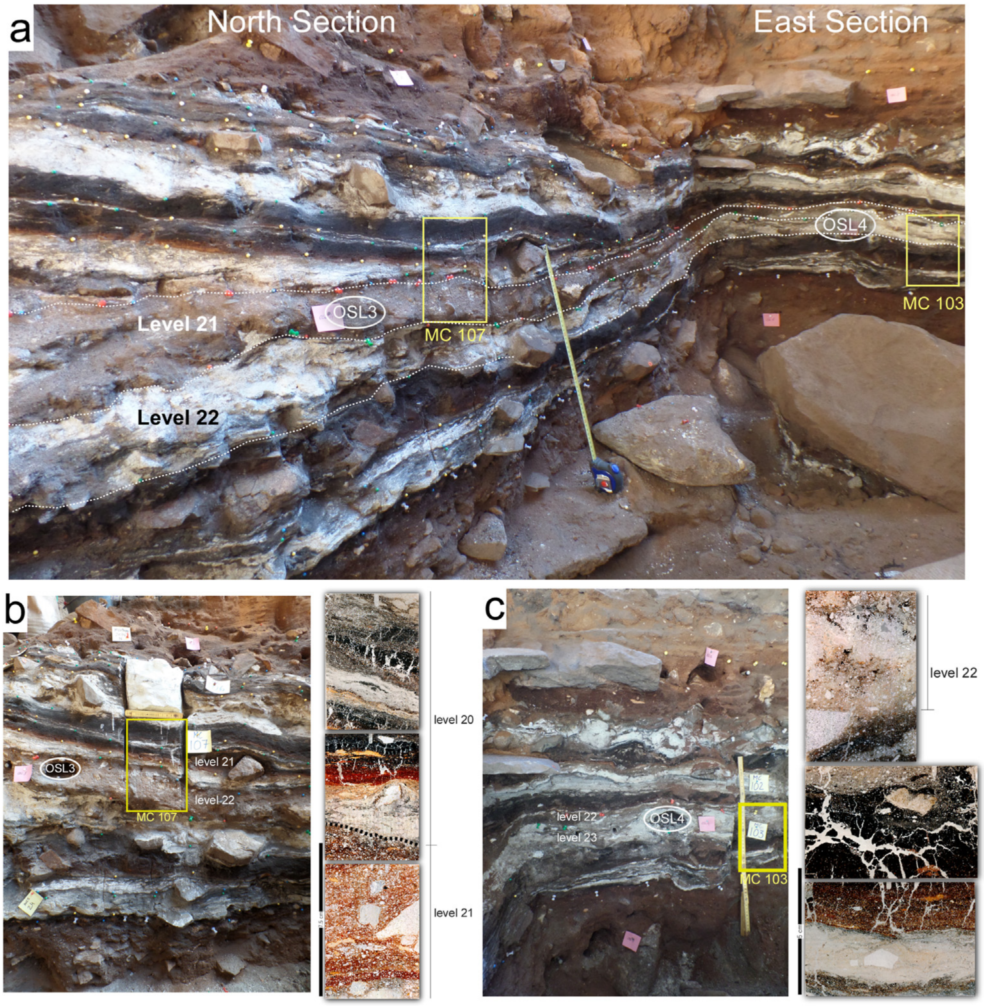

Figure 5. Location of micromorphological and optically simulated luminescence (OSL) samples. (a) View of the stratigraphy along the North and Eastern Sections. Note how level 21 thins out toward the East; that is, toward the opening of the cave. (b) Left: field view of sample 107 and its relationship with the OSL sample OSL 3 (L-EVA1468); right: thin sections produced from Montagu Cave (MC) 107 and their associated levels, namely level 21 sampled in the lower thin section corresponds to the same deposits sampled for dating. (c) Left: field view of sample 103 in the East Section and its relationship with the OSL sample OSL4 (L-EVA1467); right: thin sections produced from MC 103 with level 22 displayed in the upper thin section (corresponding to the OSL 4 sample for dating).

Micromorphological samples were carved out of the profiles and wrapped with plaster to ensure their stability. The samples were then dried for several days and impregnated with a mixture of styrene, resin, and a catalyst. From these indurated blocks, thin sections were produced by Spectrum Petrographics (Vancouver, USA). The thin sections were analyzed using a Nikon LV 100ND petrographic microscope at several magnifications and in plane- and cross-polarized light using NIS Elements v. BR. 5.30.07. Micromorphological descriptions follow established nomenclature of Stoops (2001) and Courty et al. (1989).

2.3. Technological description of stone artifacts

An overview of the stone artifacts pertaining to the relevant dated layers focuses here on classification and broader industrial attribution. The broader technological characteristics of the assemblages in terms of industrial affiliation, and the geochronology of the occupation, are key points of discussion. Therefore, a more detailed techno-functional description of Acheulean LCTs (cleavers and handaxes) is additionally presented ($n = 183$ pieces with known stratigraphic attribution), which is intended to document how different phases of production and maintenance characterize the working zones on the tools. Basic technological attributes of LCTs are presented for comparative purposes with other local southwestern Cape Acheulean assemblages, in addition to published data from Fauresmith assemblages (characteristic later Acheulean/early MSA bifaces) and bifaces from some earlier Acheulean southern African contexts.

2.4. Luminescence dating

Luminescence dating methods are used to determine the last sunlight exposure of sediment grains and hence to reconstruct the depositional history of layers surrounding archaeological assemblages. This enables reconstruction of the timing of hominin activity. The absence of K-feldspar in the Acheulean sedimentary sequence at MC, related to the site location within a quartzite mountain range, limited the luminescence dating applications to quartz techniques. Due to saturation of the natural quartz OSL signal when using the common single-aliquot regenerative dose (SAR) approach (e.g., Murray and Wintle, 2003), the thermally transferred optically stimulated luminescence (TT-OSL) signal (Wang et al., 2006a, 2006b, 2007) was used to determine the equivalent dose (D_e) at MC. The TT-OSL signal has been shown to grow to higher doses than the OSL signal, with natural saturation doses between 702 Gy and 1261 Gy reported by Neudorf et al. (2019). The two main challenges when dating the TT-OSL signal are 1) the signal intensity is typically lower than that of OSL and 2) it is slow to bleach; therefore, requiring a longer duration of sunlight exposure to reset the natural signal (e.g., Tsukamoto et al., 2008; Duller and Wintle, 2012; Arnold et al., 2019; Neudorf et al., 2019). The issue of slow bleaching can be circumvented by using a modern sample to measure a residual that can then be subtracted from the natural De prior to age calculation (e.g., Neudorf et al., 2019). However, if a suitable modern sample is not available, the use of the TT-OSL signal should be limited to sedimentary sequences that have been subjected to sufficiently long periods of sunlight exposure during transport or following deposition.

The sediments within MC are interpreted to derive mainly from inside the cave system, though contain substantial inclusions such as phytoliths, archaeological materials, and seed casts that derive from outside the cave. Quartzite grains resulting from rock-weathering processes inside the cave may have undergone several cycles of transportation and deposition/redeposition within the cave system. In which case, the bleaching event/s most likely occurred after the sand grains had been deposited at or near the cave entrance. Transport of the quartz grains to the cave entrance (i.e., the sampling location) is interpreted to have occurred in single events, as evidenced by the thinly laminated sublayers of the MC archaeological sequence. Furthermore, it is realistic to assume substantial sunlight exposure at the cave mouth during site occupation in the Middle Pleistocene. The area occupied in the Middle Pleistocene is today subjected to seasonally variable but substantial sunlight and, combined with the presence of in situ diatoms in the Acheulean deposits that rely on substantial direct sunlight exposure to grow, additionally support the likelihood of sunlight in the cave when these levels were accumulating (Fig. 6). Thus, we assume that the quartz grains received sufficient sunlight exposure to bleach the TT-OSL signals to an acceptable level.

Samples, equipment, and measurement protocols Samples were collected in light-tight metal tubes and were sealed for transportation to the lab. All sample preparation was completed under subdued red-light conditions. The sample preparation of the coarse-grain quartz fraction included the common steps of chemical treatment with 10% hydrochloric acid (HCl) and 30% hydrogen peroxide (H_2O_2) to remove carbonates and organic components. Pure quartz was separated from other minerals by using sodium polytungstate solutions (2.62 and 2.70 g/cm^3). The quartz-rich fraction was etched for 60 min with 40% hydrofluoric acid (HF). Finally, the remaining quartz was re-sieved to exclude grains <180 μm in size.

All measurements were made on an automated Riso TL/OSL DA-20 reader using a calibrated ^{90}Sr/^{90}Y beta source with a dose rate of 0.112 Gy/s. Optical stimulation used Nichia NSPB500AS blue LEDs (470 nm; 87 mW/cm^2) with detection by an EMI 9235QA photomultiplier fitted with a 7.5-mm thickness Hoya U340 glass filter. TT-OSL measurements were made on 3-mm aliquots of 180–250 μm quartz using the SAR protocol of Stevens et al. (2009) with a high-temperature clean-out step at the end of each cycle. Dose–response curves were best fit with either a single saturating exponential function or a single exponential plus linear function. Equivalent dose values were determined by integrating the initial 2 s of the decay curve after an early background subtraction, taken from the following 5 s. Acceptance criteria required individual aliquots to have a recycling ratio within 10% of unity, recuperation less than 5% of the natural signal, and a maximum test-dose error of less than 10%. The Average Dose Model (Guérin et al., 2017) was used to determine the representative value for each De distribution used in the age calculation.

Dose recovery experiment The ability of a sample to successfully recover a known beta dose is commonly used to assess the suitability of an OSL sequence to accurately date a suite of samples (Wintle and Murray, 2006). A dose recovery test usually requires the natural OSL signal be bleached from the aliquots prior to irradiating them with a known beta dose. The known dose is then treated as an unknown and measured as if it were a natural D_e. The resulting D_e value is used to calculate the ratio between the measured dose and the given beta dose; a ratio between 0.90 and 1.10 is considered successful. However, as discussed earlier, the TT-OSL signal is very slow to bleach (e.g., Neudorf et al., 2019). Therefore, instead of attempting to bleach the signal, the ability of sample L-EVA-1467 to recover a dose was tested by adding a known beta dose on top of the natural signal (i.e., Natural + β). Ten aliquots were prepared and given a known beta dose (150 Gy) in addition to the natural signal. The D_e (Natural + 150 Gy) was measured for each aliquot, and a residual dose representing the natural signal (in this case the natural D_e for the sample: 271 ± 19 Gy, $n = 35$) was subtracted from the measured value (407 ± 35 Gy). Thus, the residual-subtracted D_e value (136 ± 15 Gy) yielded a dose ratio of 0.91 ± 0.10, which demonstrates the ability of the SAR sequence of Stevens et al. (2009) to recover a known beta dose in the current study and, therefore, its suitability to date the samples from MC.

Dose rate calculation To obtain the nuclide concentrations of U, Th, and K, high-resolution (low level) gamma spectrometry was applied at the Felsenkeller laboratory (Dresden, Germany) on an N-type detector. A water content of 10 ± 5% was assumed, based on the current morphology of the cave entrance relative to the area from which the samples were extracted, which is exposed to extremely limited precipitation. Importantly, such contexts potentially change at geological timescales, which is why an error is added to this value to control for these uncertainties. To account for cosmic ray contribution (Prescott and Hutton, 1988), the altitude above sea level (a.s.l.), the geographical coordinates, as well as the sediment thickness above the sampling point were taken into account. For the sediment thickness component, we also integrated the rock thickness of the quartzite formation capping the site, resulting in a negligible cosmic dose rate contribution.

Regional Middle Pleistocene ages by biome Distributions of Late and Middle Pleistocene age estimates <1 Ma in southern Africa were plotted by vegetation biome to better assess how the new ages from MC fit with what is known more broadly from southern Africa. Data were acquired from the ROCEEH Out of Africa Database (https://www.roceeh.uni-tuebingen.de/roadweb/smarty_road_simple_search.php) by selecting an age range from 999 ka to 50 ka and then extracting biome affiliation of each dated location from available vegetation maps (see Fig. 1), using functions in the Raster R package v. 3.4.5 (Hijmans et al., 2020; Kandel et al., 2023). Violin and boxplots were used to visualize the contrasts between the Fynbos and Savanna biomes of southern Africa. The aim here was to visualize distributions of MSA and Acheulean ages to assess broadly differential patterns of overlap between earlier MSA and Acheulean occupations in different vegetation biomes and to visualize whether the MC ages are unexpected given this spatial and temporal context.

2.5. Phytolith analysis

Phytolith analysis has a key role in the study of the otherwise largely invisible paleobotanical record at MC as these traces are highly durable in acidic sedimentological contexts, and thus are often preserved in sediments over long periods of time (Piperno, 2006). Phytoliths were extracted from four sediment samples across the lower Acheulean levels as documented in the 1964 stratigraphic nomenclature (levels 20–24; Figs. 2 and 5) so as to

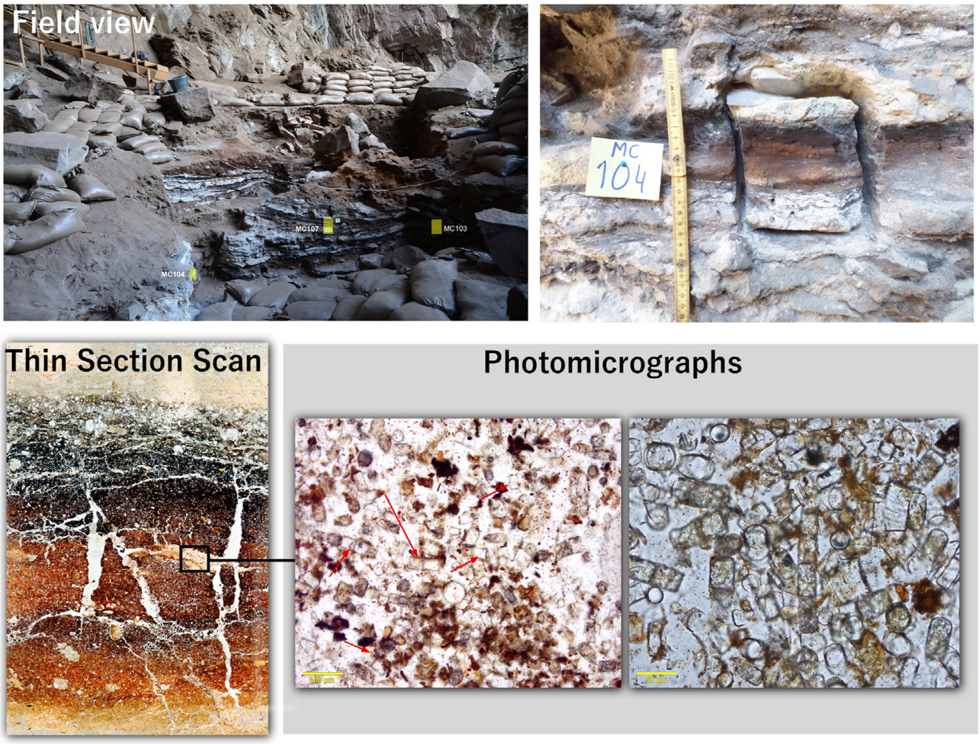

Figure 6. Micromorphological sample Montagu Cave (MC) 104. Top left: field perspective of micromorphological sample locations discussed in the text. Top right: Micromorphological sample MC 104 immediately prior to extraction from the western section, which has diatom rich stratigraphic layers. Bottom left: thin section scan of diatom rich layer within sample MC 104. Bottom right: photomicrographs of semi-articulated diatoms comprising much of this layer.

link the ages and micromorphological samples in this part of the site. A modern reference sediment sample was taken in the natural environment on the slope of the mountain where the cave is located, ~150 m from the cave opening.

The investigation of plant silica remains focused here on the proportional representation of grass silica short cell (GSSC) phytolith morphotypes to derive paleoenvironmental information from four consecutive archaeological layers that encompass the dated occupations discussed in this paper. The focus on GSSC morphotype representation acknowledges that the biogeographical distribution of southern African grass subfamilies is controlled primarily by a wide range of biomes that are all strongly linked to variable rainfall regimes, growing-season temperatures, and elevation. GSSC studies thus reasonably assume phytoliths to be suitable indicators of habitat variability (Vogel et al., 1978; Ellis, 1980; Gibbs Russel et al., 1990; Mulder and Ellis, 2000; Mucina and Rutherford, 2006). The southern African local potential of modern phytolith assemblages as proxies for paleonvironmental reconstruction has been well established through area-based, modern surface soil phytolith assemblages as comparative analogs (Cordova and Scott, 2010; Mercader et al., 2011; Cordova, 2013; Esteban et al., 2017) and also through the use of actualistic data to interpret fossil grass phytolith assemblages according to their association with known ecological requirements of the grass species that produce them, irrespective of taxonomic affiliation (Rossouw, 2009, 2016; Chazan et al., 2012). Plant modern material studied and drawn on to interpret the four archaeological samples from MC derive from Rossouw (2009), and relevant data and description tables available therein.

Phytolith extraction Five 1-g archaeological sediment samples, including one modern soil sample for comparison, were prepared for phytolith extraction following a combination of steps selected from previously published protocols (Lentfer and Boyd, 1998; Albert and Weiner, 2001; Horrocks, 2005; Katz et al., 2010). These steps entailed deflocculation, removal of carbonates and organic material using a 10% HCl and concentrated nitric acid (HNO_3) solution. For mineral separation, the acid-insoluble fractions were centrifuged using a 2.4-g/ml sodium polytungstate ($Na_6[H_2W_{12}O_{40}]$) solution to concentrate phytoliths in the supernatant using a repetitive process until the supernatant was visibly clear. Approximately 1 mg of each of the samples was mounted in glycerine jelly on glass slides and examined microscopically under transmitted light using a Nikon 50i polarizing light microscope at 400× and 1000× magnification. An a priori-defined limit for counts was set at 250 GSSC phytoliths per slide (following the sampling protocol described in Rossouw, 2009). In addition to GSSC morphotypes, only phytoliths confidently recognizable at the family taxonomic rank were recorded. Amorphous plant silica bodies, morphologically characteristic phytoliths of unknown origin or nongraminoid monocotyledonous phytoliths, were not analyzed.

Identification and classification The Poaceae produces three major classes of GSSC morphotypes, namely, Lobates, Saddles, and Trapeziforms, which are umbrella terms used to include a range of morphologically diagnostic morphotypes. Phytolith analyses were based at the outset on a survey of 11 morphologically distinct GSSC morphotypes (Twiss et al., 1969; Mulholland and Rapp, 1992; Barboni et al., 1999, 2007; Runge, 1999; Piperno, 2006, 2014; Rossouw, 2009; Supplementary Online Material [SOM] Table S1). In addition to published descriptions, morphological identification of GSSC morphotypes was also based on grass phytolith reference material from an extensive plant phytolith reference collection kept in the Florisbad Quaternary Research Department at the National Museum in Bloemfontein, South Africa.

Phytolith analysis Environmental significance of GSSC phytoliths to variability in southern African grasses was assessed using a sample of 300 modern voucher specimens comprising eight subfamilies, 19 tribes, 102 genera, and 300 species. Five centimeter leaf sections were dry-ashed and mounted on slides, with each slide representing one species. Biogeographical data for each species were obtained from the National Herbarium Computerized Information System (Gibbs Russel, 1985; Gibbs Russel et al., 1990). The latter is a robust vegetation database that includes ecological and distribution data of over 1800 grass species, based on the records of more than 62,000 grass specimens collected in South Africa. This system provides a checklist of grasses that occur in each of the 3900 quarter-degree grids that cover South Africa (Gibbs Russel et al., 1990).

A fundamental concern relating to phytolith production in the Poaceae is the production of either a particular phytolith morphotype by many taxa (redundancy), or a variety of morphotypes by one taxon, otherwise known as multiplicity (Rovner, 1983). To address this issue in the context of the current analyses, a protocol was used to standardize observations by ignoring taxonomic affiliation. Each slide was thus transformed into a numeric profile based on the occurrence of 11 diagnostic GSSC morphotypes (SOM Table S1). This essentially comprises a frequency table documenting the strength of association between morphotype variability and ecological factors (SOM Table S2). Numerical profiles for ecological categories were created by combining ecologically similar species into subsets under the factors of biome (Desert, Succulent Karoo, Nama Karoo, Savanna, Grassland, and Fynbos) and edaphic conditions (montane grasses, high altitude grasses, swamps/vleis, damp soils, and shade). The procedure was repeated by counting a maximum of one hundred individual GSSC phytoliths per slide to ascertain the relative abundance (rate of production) of each of the eleven morphotypes and to test for significant differences in the relative abundance of GSSC morphotypes counted for each ecological category.

At the outset, two one-way analyses of variance (ANOVAs) were conducted to assess the effects of phytolith morphotype relative abundances on distinguishing 1) southern African biome levels (SOM Table S3) and 2) edaphic conditions (SOM Table S4). In other words, separate ANOVAs were fitted with biome and edaphic conditions as separate response variables. The reliability of morphotypes documented to be significant in the ANOVAs was further assessed with post hoc Tukey Honest Significant Differences (HSD) tests. The aim here was to document and isolate the morphotypes that had relatively greater effects in differentiating between ecological categories (biome levels or different edaphic conditions). For the ANOVAs, the alpha level was set at 0.05 with adjusted p-values being significant at $p < 0.05$.

To summarize, this analysis focuses on the biogeographical distribution of multiple grass species ($n = 300$). The morphotypes that were determined by ANOVA to be significant in differentiating biome and edaphic conditions (in separate ANOVAs) were used for decomposition of the phytolith frequency data using principal components analysis (PCA). The archaeological data were plotted on the PCA to visually assess the relative association of the archaeological samples in two separate ecological scenarios (by the factors of biome and edaphic conditions). The contributions of specific morphotypes to matrix decomposition were visualized with PCA biplots. The PCA plots and data management procedures were conducted in R v. 4.0.4 (R Core Team, 2021).

3. Results

3.1. Site formation and micromorphological observations

While a more complete view of the deposits and their formation pathways is still ongoing for the sequence of MC, here we focus on the lower Acheulean package, specifically emphasizing depositional and sedimentological characteristics of Levels 21 and 22 (Table 1; Fig. 2).

One of the most striking aspects of the lower Acheulean deposits at MC are the well-developed undulating laminations with alternating red, black, and white lenses. These deposits are rich in phosphates and have frequent inclusions of small seed coats throughout. Other common components are sand and silt-sized quartz and feldspars, as well as larger sandstone clasts that can have several degrees of weathering. While the specific nature of each of these laminations is under study, it is clear based on field and microscope observations that significant components of these laminations relate to successive accumulations of guano (either bird- or bat-derived) at the site. Interspersed with the organic-rich laminations are more clastic-rich, reddish-brown sands, the most prominent of which is Level 21.

Level 21 comprises medium loose, reddish brown coarse sands with scarcely distributed stones, which are commonly weathered and up to 7 cm in size. This stratigraphic layer is thicker toward the west (with a maximum thickness of 12 cm) and pinches out toward the east/southeast in the area of sample MC 103 (see Fig. 5). The upper 3 cm of Level 21 has a darker, redder hue and incorporates yellow quartzite granules of up to 1 cm in diameter. Under the microscope (see Fig. 7), Level 21 comprises coarse sands, mainly composed of quartz, centimeter-sized sandstone fragments, black amorphous organic fine material, and common, dispersed seed casts. Crude laminations can be observed within the layer, varying in terms of organic matter content. Relative to other layers observed in the lower Acheulean deposits, however, Level 21 is richer in siliciclastic materials and is relatively deprived of organic matter, which can be an indication of a relative decrease in the rate of guano accumulation vs. geogenic inputs at this time.

Level 22 has a stringing white powdery color and is composed of loose sands with common sandstone fragments that are up to 20 cm in diameter, particularly toward its base. Locally thin (1–2 cm), black laminations occur. The thickness of the layer varies across the profiles and is ~6 cm thick in the sample 103 location (see Fig. 5). Under the microscope, the top of sample MC 103 shows a succession of distinct microlayers that vary in terms of color and content (Figs. 5 and 8). The top of the thin section is composed of loose, white coarse sands with a porphyric coarse/fine distribution and abundant packing voids. Here, and throughout the thin section, authigenic radial phosphates (identified by FTIR to be leucophosphite minerals) are present and have different degrees of dissolution throughout the deposits. These deposits rest on crudely bedded coarse and fine sandy lenses that vary in their content of amorphous organic fine material. The origins of the coarse quartz sands relate to arenization of the cave's bedrock, whereas the organic materials likely derive from local guano deposits, resulting in acid pH conditions that enable the formation of authigenic phosphate minerals (e.g., Karkanas et al., 2000).

3.2. Stone artifacts

The available lithic assemblage from Levels 21–22 of Keller's excavation, as well as the lithics recovered from equivalent layers in the 2014–2017 excavations, are dominated by LCTs and bifacial shaping by-products that are indicative of the Acheulean industry (Table 1; Figs. 3c, 9–11). The stone artifacts recovered from excavated Acheulean layers are made exclusively on quartzite raw materials. The morphology of cortex remnants on the artifacts indicates that this material (quartzite) likely derives from the river below the mountain upon which the site is located (Fig. 2a).

LCT production is dominant in the Acheulean layers, with low numbers of cores relative to LCTs (Table 2). While local quartzites dominate assemblages from all layers, there is a shift in core-to-

Table 1
Piece-plotted artifacts (>2.5 cm) recovered in the 2014–2017 excavations.

Artifact type	Middle Stone Age	Upper Acheulean	Lower Acheulean
Whole flakes and proximal flakes	1732	1918	2974
Flake angular fragments	170	641	256
Cores	60	15	2
Large Bifacial Cutting Tools	0	51	6
Small bifacial tools (not LCTs)	2	0	0
Hammerstones	2	5	0
Anvil	5	1	0
Retouched tools	3	5	3
Ochre	5	10	1
Quartz crystal	2	0	0
Unclassified	108	35	0
Totals	**2089**	**2681**	**3242**

LCTs = large cutting tools.

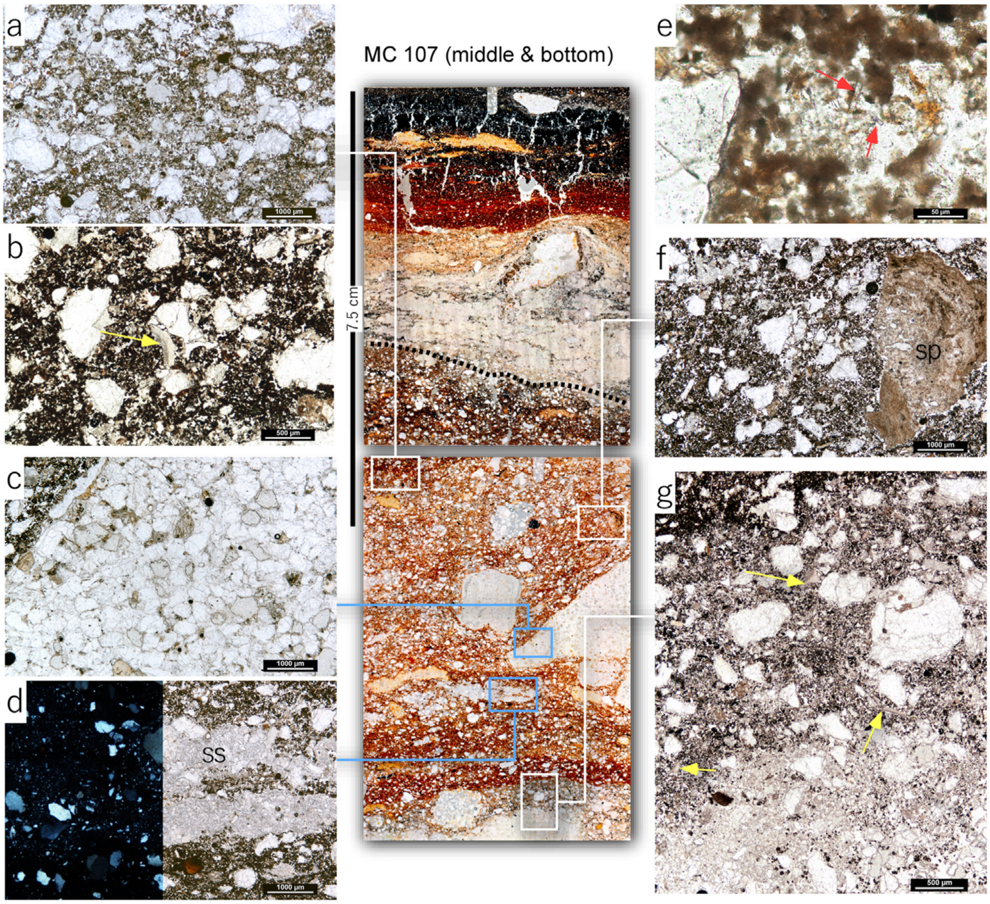

Figure 7. Level 21 in sample Montagu Cave 107. Center: thin section scans where deposits below the dashed black line correspond to level 21; white and blue boxes correspond to the location where photomicrographs were taken. (a) Photomicrograph of the upper deposits within level 21, which tend to have a darker coloration due to relatively higher content of finely dispersed organic matter, in plane-polarized light (PPL; scale is 1 mm; (b) detail of the sediments shown in (a). Note the crumb microstructure with the rich organic matrix (brown fine matrix with star-like vughs and compound packing voids) and the larger sand-sized angular quartz grains. The yellow arrow points to a seed coat, in PPL (scale is 500 μm; (c) photomicrographs of a sandstone fragment, in PPL (scale is 1 mm); (d) fragments of weathered sandstone embedded in organic-rich deposits in PPL on the right and cross-polarized light on the left. Note the undifferentiated b-fabric of these deposits in cross-polarized light (scale is 1 mm); (e) photomicrograph showing phytoliths embedded in these sediments (red arrows indicating individual phytoliths), PPL (scale is 50 μm); (f) photomicrograph showing a fragment of a silica speleothem (sp) to the right of the image, PPL (scale is 1 mm); (g) composite photomicrograph across of the bottom of layer 22 in the thin section, showing the alteration of varying composition of organic matter. Yellow arrows point to small seed coats, in PPL (scale is 500 μm). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

flake ratios between the lower and upper Acheulean layers (separated by the hiatus in occupation represented by sterile Layer 4; Fig. 4).

No technological components indicative of transitional industries, or MSA technologies, are present in the Acheulean layers. In fact, the Acheulean sequence at MC is dominated by activities related to LCT production, and clear evidence for flake or retouched tool production is comparatively minimal. Despite the relatively young age of the Acheulean occupations, the LCTs from MC differ from typical Fauresmith LCTs in terms of 1) the frequency of LCTs at the assemblage level, 2) the relative abundance of cleavers, and 3) the large size of the LCTs at MC that are more similar to local earlier

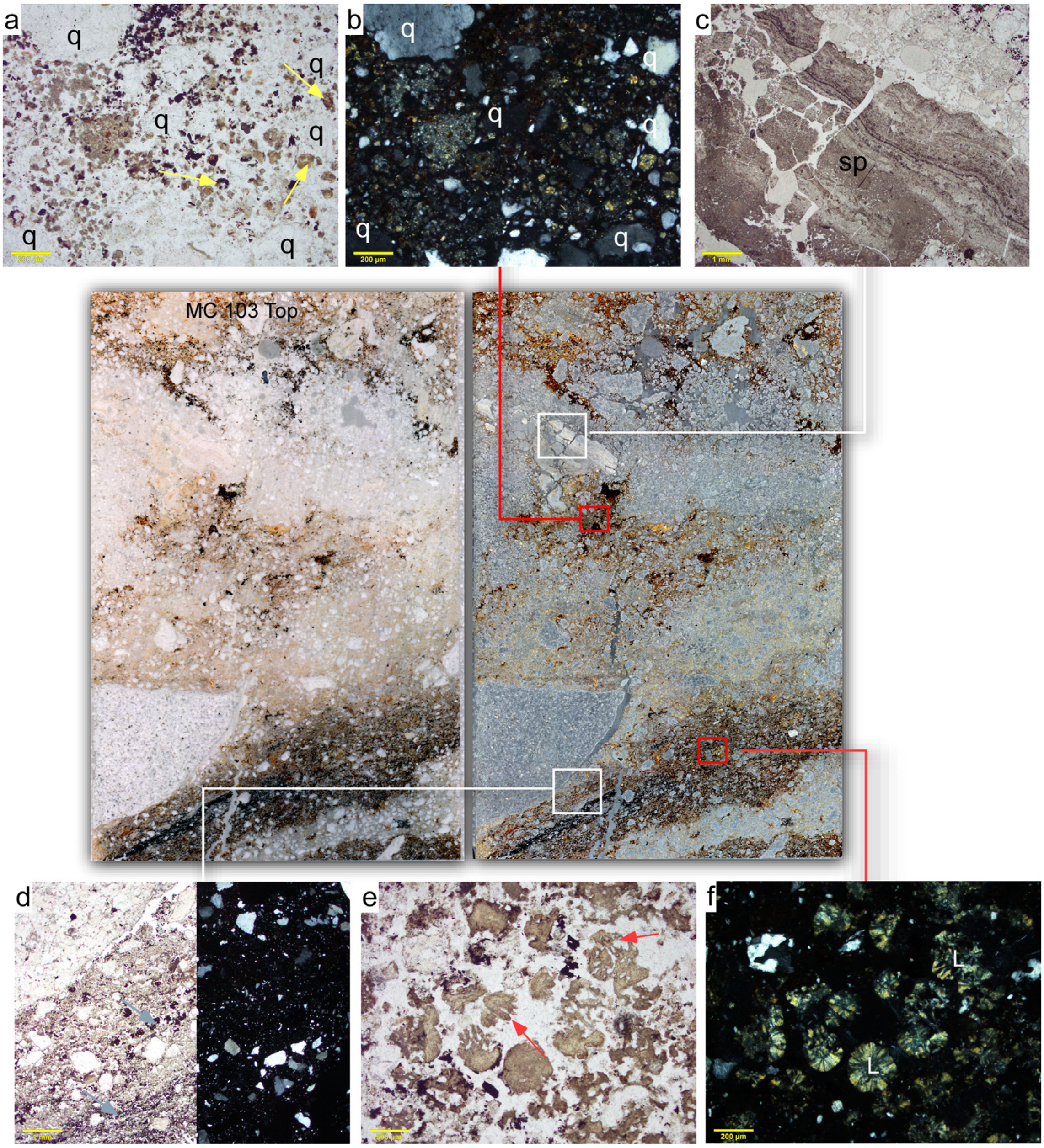

Figure 8. Level 22 in sample Montagu Cave 103 Top, where the thin section scans in normal light (left) and dark field (right) are shown; white and red boxes correspond to the location where photomicrographs were taken. (a) Photomicrograph showing the presence of authigenic phosphate minerals (yellow arrows), subangular quartz grains (q), and high porosity (void space white in this view), in plane-polarized light (PPL; scale is 200 μm); (b) same as (a) but in cross-polarized light (XPL), note the subangular quartz grains (grains with interference colors that vary from white—gray—black; void space is black in this view); (c) view of the opal speleothem with clear laminated layers, in PPL (scale is 1 mm); (d) photomicrograph of the contact between laminations of white sands and lenses with increased amorphous organic fine material (red arrows) in PPL (left) and XPL (right; scale is 1 mm); (e) detailed view of leucophosphite minerals present in the area shown in (d). Note the dissolution features (red arrows), PPL (scale is 500 μm); (f) same as (e) but in XPL. Note the well-developed radial birefringence of the leucophosphite minerals (some labeled L in the figure). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Acheulean LCTs from Elandsfontein than to published Fauresmith handaxe sizes (Fig. 9).

The typological spectrum of LCTs at MC is dominated by cleavers, although this statistic is challenging to quantify as classical-looking cleavers at MC grade into classical looking handaxes on a morphological continuum as the so-called cleaver blade is reduced, through maintenance, inwards from the two lateral edges (e.g., Fig. 10d).

Apart from the cleavers, two broad LCT morphological groups are present in the MC collection. The first group is a ‘Ficron-like’ biface variant, which is unusual for LCT collections in the southwestern Cape, with a defined tip, and an often clear inflection point along the edge, potentially distinguishing the active, transformative, and passive regions of this tool (e.g., Fig. 10a, d; Soressi, 2002). The second group comprises a more classic-looking ovate LCT form with a bilaterally symmetrical tip (e.g., Figs. 10a and 11c). There is not a clear correlation between these two modalities of shape and overall LCT size in the collection, suggesting that these groups may not represent variable stages of reduction on a single LCT production continuum (McPherron, 2000). Rather, the

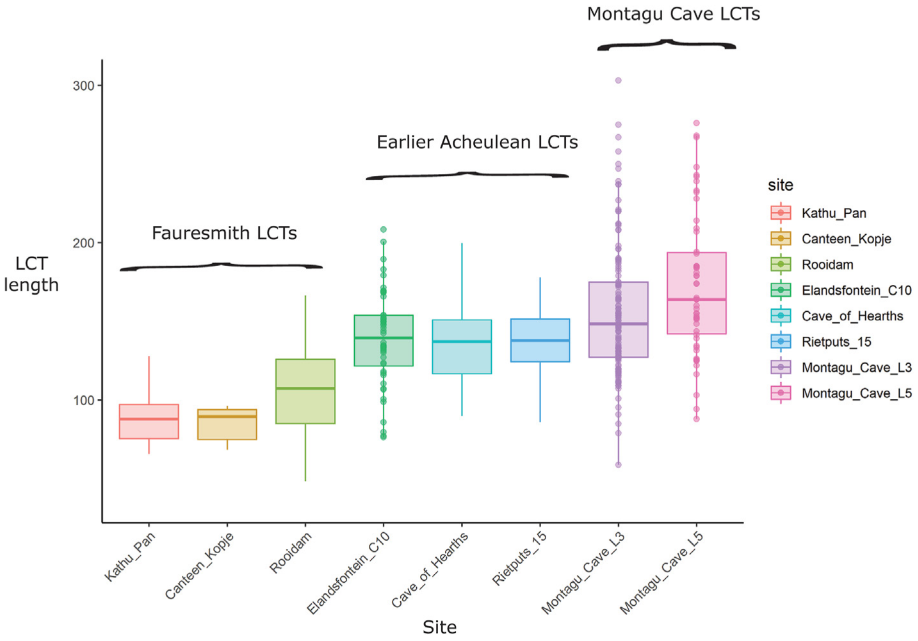

Figure 9. Box plot comparison of technological length of Large Cutting Tools (LCTs) from Montagu Cave with the local southwestern cape earlier Acheulean in situ collection from Elandsfontein Cutting 10 and LCT collections from relatively well-contextualized Fauresmith sites. For plotting purposes, Fauresmith and earlier Acheulean LCT data are simulated from summary distributions available in the literature (Humphreys, 1970; Kiberd, 2006; Wilkins and Chazan, 2012; Kuman et al., 2020; Caruana and Lotter, 2022). The solid line in each box displays the median of each assemblage; the two box hinges correspond to the first and third quartiles, whereas the two whiskers extend to 1.5x the interquartile range of each LCT length distribution. The plot illustrates that in terms of LCT length, despite the late age of the site, LCTs from Montagu Cave are more similar to early Acheulean LCTs than to late Acheulean LCTs from Fauresmith sites.

morphological variability between these two groups may be associated with a differential distribution of passive and active working edges. However, the stage of reduction at which the discussed LCT reduction trajectories diverge requires further exploration.

What characterizes ‘Ficron-like’ LCTs from MC and distinguishes them from ovate forms is that the former ones often have globular bases with sinusoidal bifacial edges characteristic of hard-hammer alternating bifacial rotation or bifacial reworking, whereas the tips have removals that are characteristic of soft-hammer thinning in terms of invasiveness and in the even distribution of thickness of these removals. The basal region in the majority of specimens embodies the maximum weight of the tools, with the tip region lighter and more extensively thinned as indicated by generally thinner and straighter edges associated with refinement (‘finition’) aimed at regularizing bilateral symmetry, as indicated also by more acute edge angles. This weight distribution between base and tip plausibly impacted on the balance between active and passive zones of the tools in a functional sense. The active zone in most specimens is represented by a tip edge with an acute, consistent, and homogenous edge angle of <30°. This angle of the working edge was created on many specimens with stepped finishing bifacial removals and can be seen in cross-sectional morphology on several specimens (Figs. 10a and 11c). This angle of the working edge in association with abundant stepping suggests that the working edge angle was the technological priority in these series of removals, rather than any anticipated future need for edge rejuvenation. In the majority of biface specimens, the refinement of the working edge is distributed intermittently on unworked edge portions that also retain the edge of the original flake blank, which is suggestive of substantial investment in initial blank production (the need for a flake edge of 30° or less as this will potentially be incorporated in the intended form of bifacial tool).

There are several shared technological traits between cleavers and handaxes in the MC LCT collection, suggesting that these forms may not have been functionally discrete from one another. For instance, in both ovate and Ficron-like biface forms, multiple specimens have one tool edge that is completely unretouched, while the opposing edge exhibits intensive series of bifacial finishing removals. Interestingly—in the context of single tool forms—in the aforementioned specimens, the mean edge angles of bifacial and unworked edges are largely quantitatively indistinguishable, implying that the decision to bifacially refine an edge or not may be driven by functional constraints (i.e., working edge angle) related to edge sharpness. Additionally, a number of ovate handaxe forms exhibit evidence of a single, or multiple tranchet blows initiating from the tip. These blows appear to be aimed at either initially refining or rejuvenating the tool edge to create a straight-looking profile morphology. Such repetitive emphasis on a single edge is rare in African Acheulean LCTs and in some ways resembles aspects of the Middle Paleolithic Keilmesser-Concept (Weiss et al., 2018).

3.3. Luminescence dating

Natural equivalent dose measurements Preliminary measurements were made on four samples from MC. As expected, the signal intensity of the TT-OSL signal was several orders of magnitude lower than that of the OSL signal for the same aliquot (data not shown). Ultimately, only two samples produced TT-OSL signals of sufficiently high intensity for dating (Fig. 12, inset). For sample L-EVA-1468 from archaeological level 21, a total of 96 aliquots were measured, and only 59% ($n = 57$) of those passed the acceptance criteria, with a further 17% ($n = 16$) classified as being in saturation (i.e., the natural signal was larger than the maximum regenerative dose). Sample L-EVA-1467 from archaeological layer 22 performed better; a total of 48 aliquots were measured with an aliquot pass rate of 85% ($n = 41$) and a saturation rate of 13% ($n = 6$). The natural dose distributions for the two samples had similar overdispersion

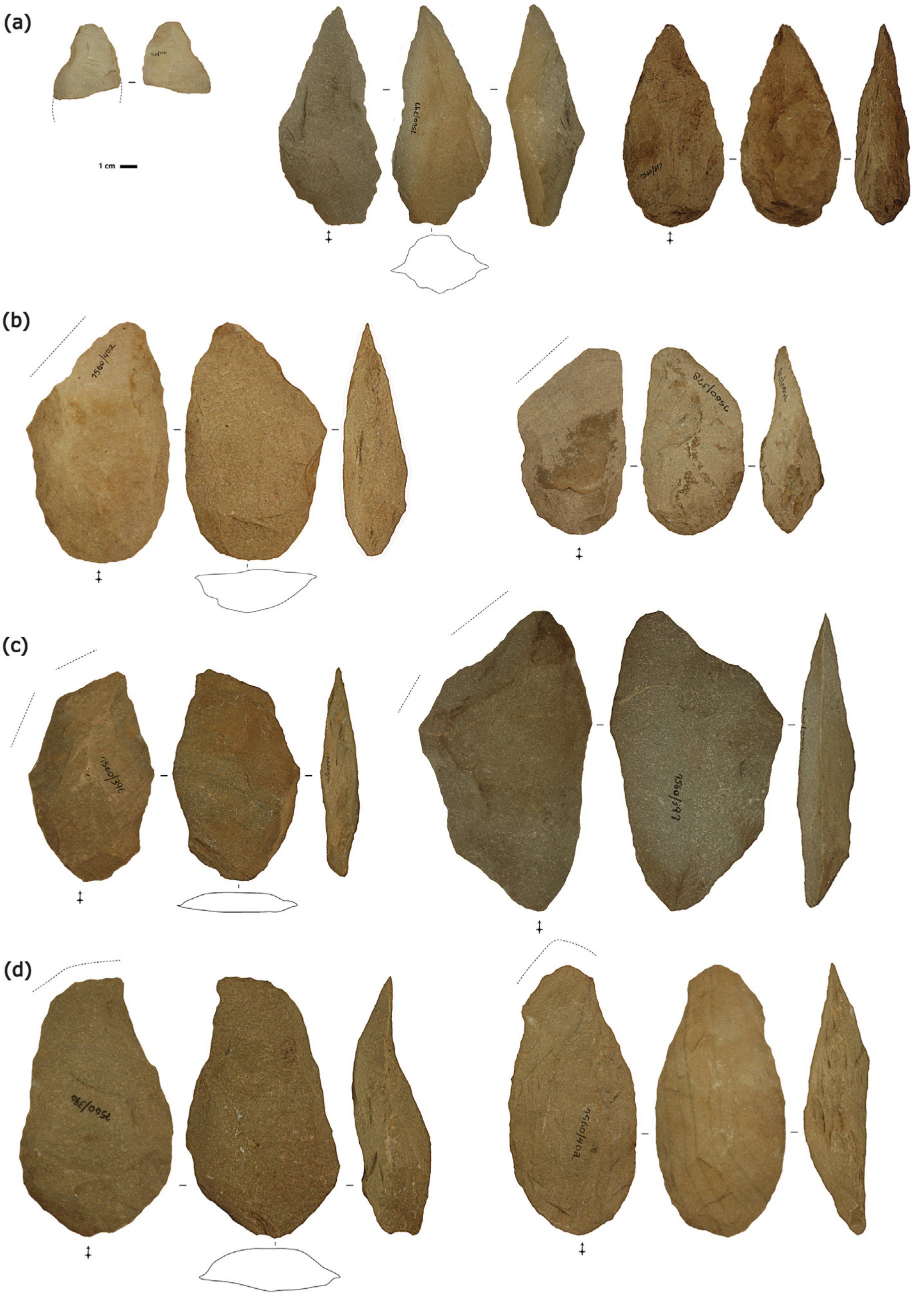

Figure 10. Selection of Large Cutting Tools (LCTS) from Layer 21 of Keller's excavation demonstrating diversity in plan and cross-sectional form in this layer. Panels (a)–(d) depict variability in LCTs excavated from Montagu Cave and are labeled for ease of reference by the technological description in the text (refer to section 3.2).

values (46% and 40%; Fig. 13). The ages (Table 2) are within uncertainty of one another; in other words, the age estimates fall within the error ranges of one another: 222 ± 31 ka for archaeological layer 21 and 243 ± 36 ka for archaeological layer 22.

There is currently no way to assess the validity of the TT-OSL ages since K-feldspar is absent and the OSL signal is saturated. Since the age range of interest is beyond the limit of radiocarbon dating and there is currently no other datable material available from MC, there is value in further geochronological work at MC, potentially to refine these ages.

3.4. Phytolith results

Grass silica short cell phytoliths and other diagnostic monocotyledonous phytoliths (Cyperaceae and Restionaceae) make up between 26% and 77% of the total number of phytoliths counted in the archaeological samples (SOM Fig. S1). The remainder consists of indeterminate phytolith types that could not be confidently identified to any taxonomic rank.

With a high C_3-to-C_4 grass ratio (otherwise known as a high Ic index; SOM Table S5), C_3-type short cells (Trapezoid, Rondel, Oblong, and Reniform) are prevalent throughout the sequence (>40% of the total short cell phytolith count) at the expense of C_4–type markers (≤12%), the latter primarily represented by medially indented, Chloridoid-type Saddle morphotypes (Variant 1), and medially convex, Aristidoid-type Saddle morphotypes (Variant 2; Fig. 14). A low Bilobate-Variant-1-to-Bilobate-Variant-2 ratio (1.8%–9.9%) aligns with the proportion indicative of modern Fynbos grasses (ratio = 11%, $n = 104$) when compared to other biomes, for example, 94% for Desert, 46% for Savanna, and 42% for

Figure 11. Selection of Large Cutting Tools (LCTs) from Layer 22 of Keller's excavation demonstrating variability in plan and cross-sectional form of LCTs in this layer. Panels a–d depict variability in LCTs excavated from Montagu Cave and are labeled for ease of reference by the technological description in the text (refer to section 3.2).

Table 2
Equivalent dose and dosimetry data for two samples from Montagu Cave including the number of aliquots measured (n), the number of aliquots that passed the acceptance criteria (n), the overdispersion, equivalent dose (D_e), the radionuclide concentrations for uranium (U), thorium (Th), and potassium (K); the dose rate (D_r) and age.

Sample ID	Archaeological layer	Measured	Passed (n)	OD (%)	D_e (Gy)	U (ppm)	Th (ppm)	K (%)	D_r (Gy/ka)	Age (ka)
L-EVA-1468	21	96	41	46	269 ± 20	1.64 ± 0.17	7.30 ± 0.5	0.46 ± 0.04	1.21 ± 0.14	222 ± 31
L-EVA-1467	22	48	35	40	271 ± 19	1.59 ± 0.25	7.20 ± 0.5	0.37 ± 0.04	1.12 ± 0.15	243 ± 36

Grassland (Rossouw, 2009). In the archaeological samples from MC, Polylobates are absent and Cross morphotype proportions are low (≤1% of total short cell phytolith count) compared to proportions in the modern soil sample from the Montagu region (3.9% and 2.5%, respectively) and the Fynbos experimental group (3.8% and 3.2%, respectively).

One-way ANOVA followed by post hoc HSD tests indicate that the relative abundance of Bilobate Variant 1, Saddle Variant 1, Saddle Variant 2, Trapezoid, and Reniform morphotypes had significant effects in differentiating between biomes, while frequencies of Polylobate, Trapezoid, and Reniform morphotypes were significant for differentiating edaphic conditions (SOM Table S4).

Variability in the GSSC morphotype frequencies that were documented with statistically significant effects (as described above) were visualized with two PCAs (Fig. 15). Principal component 1 (PC1) for Biome accounts for more than 57% of the variance, where predominant photosynthetic type ($C_{3,}$ C_4) and ambient growing temperature autocorrelate accordingly between winter (high-positive loadings for Reniform and Trapezoid morphotypes) and summer rainfall conditions (high-negative loadings for Bilobate Variant 1 and Saddle Variant 1), respectively (Fig. 15a). This axis generally reflects discrimination of short-cell phytoliths based on grasses following either the C_3– or C_4–NADP/C_4-PCK photosynthetic pathway. Negative loadings for the Reniform and high-

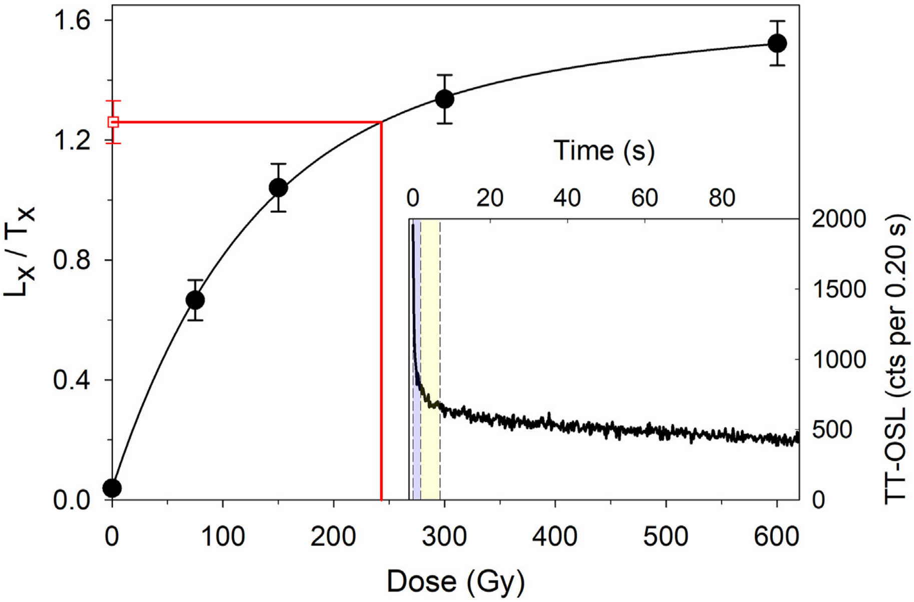

Figure 12. This figure illustrates a representative dose–response curve for one aliquot of sample L-EVA-1467, with a sufficiently high intensity for dating. The natural L_n/T_n measurement (red square) and extrapolated equivalent dose (D_e) shown in red. Inset: the natural thermally transfered optically simulated luminescence signal for the same aliquot reported as counts (cts) per 0.2 s. The D_e was obtained by integrating the initial signal (shown in blue) after subtracting an early background (yellow). Lx/Tx (y-axis) refers to the normalized luminescence signal. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

positive loadings for Saddle Variant 2, represent a rainfall gradient on PC2. The Saddle Variant 2 makes up ≥24% of the GSSC component in the desert and succulent Karoo biomes ($n = 72$) and ≤5% of the GSSC component in the savanna and grassland biomes ($n = 291$).

Principal component 1 for the different edaphic conditions plotted accounts for more than 64% of the variance, with damp soils/swampy conditions ($n = 54$) characterizing high PC1 values and high-altitude and montane grassland conditions ($n = 88$) plotting at the negative PC1 extreme (Fig. 15b). Principal component 1 for the different edaphic conditions likely represents a moisture gradient between drier (negative loadings for Trapezoid and Reniform) and wetter soils (positive loadings for Polylobate and Cross; Fig. 15b). Ordination of the MC GSSC phytoliths for biomes provides a paleoenvironmental signal that is consistent with C_3, winter rainfall conditions analogous to the modern fynbos biome for all the samples (including the dated levels 21 and 22), but with possibly lower-than-modern fynbos rainfall conditions indicated for samples from level 20. Ordination for edaphic conditions provides a paleoenvironmental signal that suggests soil moisture conditions analogous to the modern fynbos biome for all the samples (including the dated levels 21 and 22) but with possibly warmer overall temperatures indicated for samples from level 20 (Fig. 15).

4. Discussion

4.1. Summary discussion of Montagu Cave fieldwork results

Much fieldwork on the ESA of southern Africa has focused on open landscape settings and non-occupational cave contexts, primarily in the northern and central interior regions. Montagu Cave is one of the few African cave sites with Acheulean deposits and contains archaeologically dense, well-stratified layers dating to the later Middle Pleistocene. While the details of the sequence will be the focus of dedicated papers, here we have introduced the site and lower archaeological sequence focusing on descriptions of the stratigraphy and site formation processes, stone artifact characteristics emphasizing LCT production, geochronology of the lower layers, and ecological context of the Acheulean occupations focused on phytolith assemblages.

Site formation observations Sedimentation and site formation studies indicate abundant inclusions of seed coats and evidence of phosphate formation in the archaeological layers. While this avenue of research is still under study, current observations of the dated layers indicate that a key parameter in the formation of the deposits relates to successive deposition of guano which—along with the rich archaeological data—implicates probable later Middle Pleistocene cohabitation of the shelter by Acheulean hominins and bird or bat populations in the organic rich layers. Other layers, also containing substantial stone artifact assemblages, have relatively greater geogenic inputs with abundant siliclastic components. Together, these observations indicate fluctuations in the relative contributions of organic (possibly guano-related) and nonorganic elements against a relatively consistent (apart from the sterile layer) backdrop of intensive accumulation of archaeological materials.

Stone artifacts The late Acheulean stone artifact assemblages at MC are classical in nature, with no mosaic or transitional technological elements. The constrained raw-material diversity in the Acheulean assemblages—and contingent paucity of evidence for substantial raw-material transport or involvement of MC occupants in regional trade networks—is perhaps curious for a hominin occupation of <300 kyr (Kuhn, 2011; Turq et al., 2017; Wilkins, 2017). Even at the ~1 Ma–600 ka site of Elandsfontein Cutting 10, there is a substantial diversity of raw-materials indicating transport of rock for LCT manufacture over distances of at least 25 km (Archer and Braun, 2010). However, the high quality of the locally available quartzite at MC may explain the sole reliance on this material and is supported by the fact that it is the dominant raw material also in the MSA and LSA layers at the same site (Keller, 1973).

The proximity of a high-quality raw material to MC leads one to infer that hominins may have exploited local sources to procure and test raw materials and then transport blanks or shaped tools

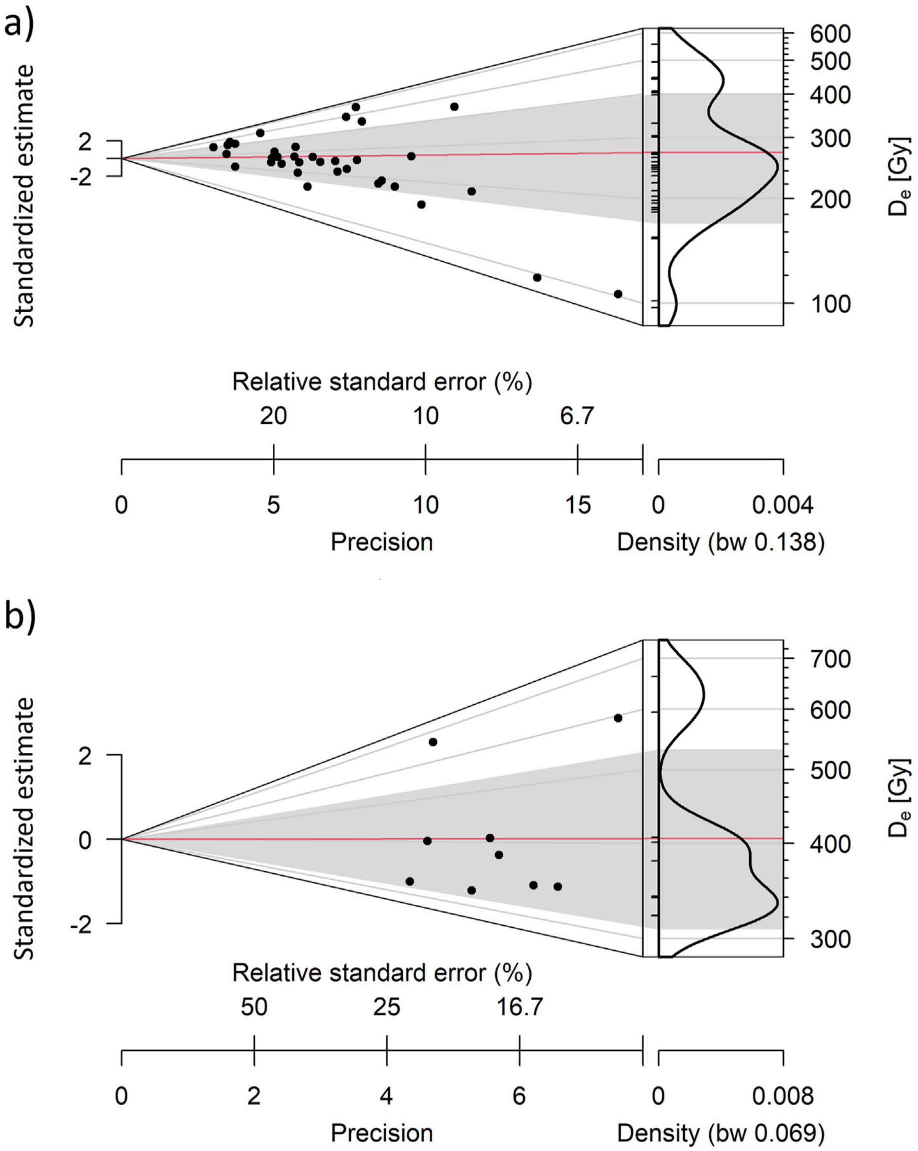

Figure 13. This figure is showing dose distributions for sample L-EVA-1467 for (a) the natural equivalent dose and (b) the Natural + β dose recovery measurements prior to residual subtraction. The red line denotes the Average Dose Model (ADM) D_e and the gray box = 1-sigma. The two natural dose distributions have similar overdispersion values, 40% for L-EVA-1467 and 46% for L-EVA-1468 (data not shown). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

away (fragmented production), or alternatively, hominins made, used, and maintained tools at a single locality on the landscape (de la Torre et al., 2014; Presnyakova et al., 2018). In the first scenario, we would expect to see only specific stages of stone tool production at MC, while in the latter, all phases of lithic production would be present. Indeed, all aspects of reduction are represented in lithics recovered from the Acheulean layers during the 2014–2017 excavations, including large cores to make LCT blanks, large unretouched flakes, LCTs in various stages of production, and recycled LCTs. Flakes associated with the initial roughing out of LCT blanks, shaping of LCTs, as well as edge retouch associated with the later stages of production are also present, suggesting substantial on-site LCT production at MC, particularly in the upper Acheulean layers (Soriano et al., 2009, 2015).

The shift in core-to-flake ratios between the lower and upper Acheulean layers may indicate a change in site use or artifact transport decisions between these occupations. The frequency of LCTs relative to cores also suggests that substantial components of flake production at MC may have been associated with LCT reduction (the production of flake forms while manufacturing LCTs), unless there was a systematic transport of cores away from the site that cannot at this stage be demonstrated. The majority of LCTs at MC were made on side-struck flakes, and boulder cores were documented in the vicinity of the cave (but not in situ within the cave) showing large negative flake scars demonstrating the systematic removal of large flakes. The use of boulder cores to produce standardized series of side-struck flakes represents a similar initiation of the LCT chaîne opératoire to what has been documented at the older southwestern Cape Acheulean site of Elandsfontein (Archer and Braun, 2010; Braun et al., 2016).

Luminescence ages in regional context The dating of MC will benefit from additional future work as newly applicable techniques hopefully become available and increasingly utilized techniques such as TT-OSL are refined and results are further validated. The geochronological research for the current project faced several challenges including the paucity of available complementary

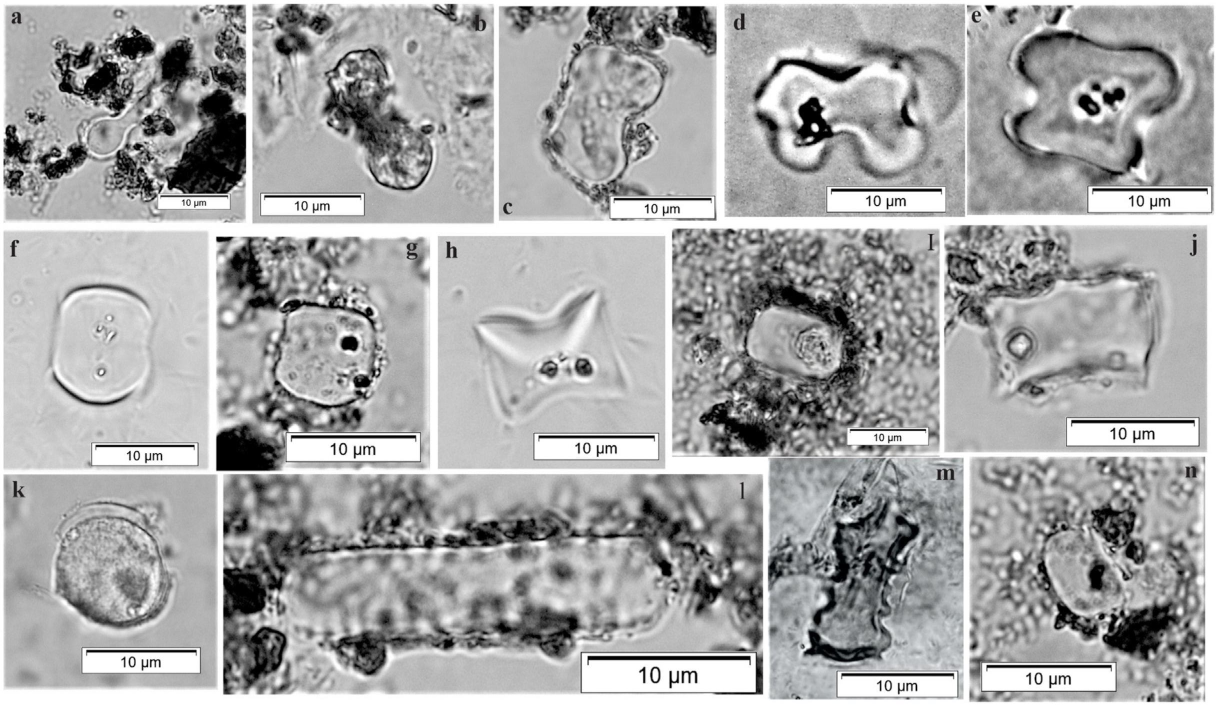

Figure 14. Photomicrographs of diagnostic grass silica short cell morphotypes identified in the archaeological samples: (a) Bilobate Variant 1, planar view; (b) Bilobate Variant 2, planar view; (c–d) Bilobate Variant 3, planar view; (e) cross, planar view; (f) Saddle Variant 1, planar view; (g) Saddle Variant 2, planar view; (h) Saddle Variant 2, side view; (i) Trapezoid, planar view; (j) Trapezoid, side view; (k) Rondel, planar view; (l) oblong smooth, planar view; (m) oblong crenate, planar view; (n) reniform, planar view.

techniques, the absence of K-feldspar in the sediments, and the saturation of the blue-light-stimulated OSL signal. The stability of the TT-OSL signal is still under debate, with some studies suggesting that a correction needs to be applied to TT-OSL ages to account for the short lifetime of the signal (e.g., Adamiec et al., 2010; Faershtein et al., 2018). However, other studies have shown that no correction is necessary (Arnold and Demuro, 2015). Furthermore, Pickering et al. (Pickering et al., 2013) reported good agreement between TT-OSL ages for sand grains embedded in tufa and U–Th ages from two flowstone layers at Pinnacle Point, another southwestern Cape cave site formed in Table Mountain Sandstone (but coastal), around 180 km southeast of MC. Thus, the ages for MC presented in this paper have not been corrected for signal stability.

Some studies have reported a difficult-to-bleach residual TT-OSL signal measured from modern samples, e.g., 10.0–18.7 Gy in Chinese loess (Wang et al., 2006a), 17.2 ± 0.8 Gy for a coastal dune (Tsukamoto et al., 2008), and 15–30 Gy for a beach sand (Pickering et al., 2013), both from South Africa (latter two examples), and 93.9 ± 5.5 Gy in aeolian dune sediments from Tasmania (Neudorf et al., 2019). While we assume the MC sediments should have received sufficient sunlight exposure to bleach the TT-OSL signal (as discussed in section 2.4), it is possible that a residual signal exists in these samples that was not accounted for, in which case, the reported ages for MC should be considered maximum ages.

As we know that MSA technologies were practiced by 300 ka in several parts of Africa, from a continental and regional perspective, the ages of ~243–222 ka for classic Acheulean assemblages at MC are reasonably young, though are not the youngest ages for classic Acheulean assemblages in Africa (de la Torre et al., 2014). When one considers distributions of Late and Middle Pleistocene ages in southern Africa by vegetation biome, however, some relevant spatiotemporal patterning in ages for MSA and Acheulean assemblages emerges (Fig. 16).

At MC, Acheulean occupations occur in MIS 7, potentially only ~80–70 kyr earlier than the oldest documented MSA in the Fynbos and Succulent Karoo biomes, in the southwestern Cape (Jacobs, 2010). The current ages for these layers at MC—and biostratigraphically inferred ages for the relatively nearby Acheulean site of Duinefontein 2—do not overlap with the existing ages for the MSA in the southwestern Cape (Fig. 16). Viewed together, the age estimates for Duinefontein 2 and MC suggest that while hominins were manufacturing MSA assemblages in the northern and central interior regions of southern Africa (Henderson, 2001; Wilkins and Chazan, 2012), populations were still making classic Acheulean tools in the southwestern Cape, wherein the oldest ages for well-contextualized MSA are only ~190–162 ka (Jacobs, 2010; Marean, 2011; Herries et al., 2022).

In the Fynbos and Succulent Karoo biomes, there is a low number of ages for the earliest—MIS 6–5—MSA industries (Wurz, 2013; Will et al., 2019), but the available ages are young relative to other southern African regions, and the late Acheulean ages in the southwestern Cape are correspondingly young (Cruz-Uribe et al., 2003; Braun et al., 2013, 2016; Caruana et al., 2023). Within the Grassland and Savanna biomes further north, the earliest MSA tends to be older than in the southwestern Cape, including perhaps transitional industries such as the Fauresmith (Chazan et al., 2008, 2020; Wilkins and Chazan, 2012), but there are correspondingly older ages for the classic later Acheulean within these northern regions (Herries, 2011). To summarize, if one compares distributions of ages for later Acheulean and earlier MSA industries between regions of southern Africa, it is clear that there is substantial overlap between these industries at the broader scale of southern Africa. But if one compares these ranges within regions of southern Africa, there does not appear to be substantial overlap between the Acheulean and MSA, for instance, within biomes (Fig. 16).

Despite the young ages for the Acheulean assemblages at MC, as mentioned already, there are no transitional aspects evident in the stone artifact assemblages. Whether or not one accepts so-called transitional industries in southern Africa as reliable technological entities, it seems likely that both the timing and nature of change

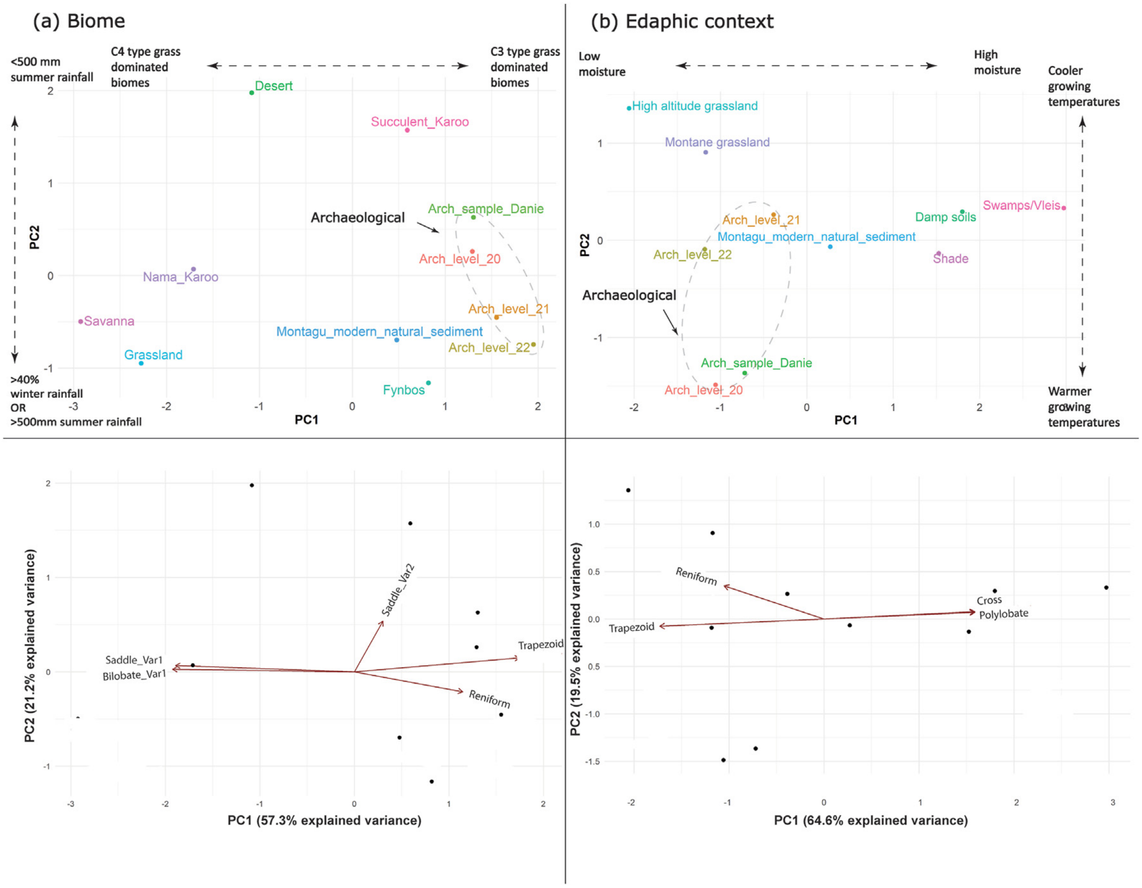

Figure 15. Principal components analysis of phytolith data from Montagu Cave relative to modern references for the factors of (a) biome and (b) edaphic context. (a) Principal component analysis of five statistically significant grass silica short cell (GSSC) morphotypes for biome affiliation (Bilobate Variant 1; Saddle Variant 1; Saddle Variant 2; Trapezoid; Reniform). The plot provides an archaeological signal that is consistent with C_3 grasses and winter rainfall conditions analogous to the modern fynbos biome for all the samples but with lower-than-modern fynbos rainfall conditions indicated for samples from level 20 and layer Danie. (b) Principal component loadings of four statistically significant GSSC morphotypes for edaphic context affiliation (Polylobate; Cross; Trapezoid; Reniform). Ordination for edaphic conditions provides a paleoenvironmental signal that suggests soil moisture conditions analogous to the modern fynbos biome for all the samples but with possibly warmer overall temperatures indicated for samples from level 20 and layer Danie.

between the late Acheulean and early MSA were ecologically dependent.

Phytolith analysis The archaeological phytolith compositions are intermediately situated in multivariate space between Fynbos and Succulent Karoo biomes, suggesting general similarities in the distribution of vegetation resources relative to a modern CFR baseline. The position of the MC phytolith samples on relative moisture and temperature gradients indicate a warmer and potentially more habitable environment than in succeeding MIS 6 (by assumption, as we do not include phytolith data from MIS 6), potentially aligning with the geochronological estimates of an interglacial occupation.

4.2. Contextualizing the late Acheulean at Montagu Cave relative to regional explanatory models

More generally speaking, stone artifacts are the most abundant cultural remnants of past hominin activity and are a key dimension to the characterization of human behavioral evolution in Africa. As lithic remains are taphonomically robust—and Stone Age artifact assemblages are almost always large—they have enabled scientists to infer broad temporal patterns of hominin adaptive change which, in potential, transcend the individual level behavioral variation upon which selection operates (Bettinger, 2009). Historically, variability in so-called technological complexes—meaning major shifts in the composition of artifact forms and production strategies through time—has been the broadest systematics drawn on to synthesize African evidence for long-term cultural change (Goodwin and Van Riet Lowe, 1929). The African Acheulean to MSA represents one such broad shift. That the Acheulean to MSA entailed advances in several dimensions of hominin material culture is seldom questioned (Klein, 2000). Yet an emerging view is that the origins of the MSA, and by implication the end of the Acheulean, may be key to exploring the behavioral origins of modern humans (Hublin et al., 2017; Richter et al., 2017; Potts et al., 2018).

In comparison to other African regions, southern Africa has a large number of MSA cave sequences dating within the last ~150 kyr. Extending this regional record back to the Acheulean, however, has been hampered by a paucity of cave contexts with relevant assemblages. One issue is that contextualized Acheulean occupations in southern Africa tend not to be in caves (Deacon, 1993; Klein, 1995). This situation may result from a combination of factors including differential landscape use between Acheulean and MSA hominins, the greater effects of post-depositional processes on older cave deposits in addition to the challenges facing available dating methods (Deacon and Deacon, 1999; Surovell and Brantingham, 2007; Herries, 2011; Guérin et al., 2013). The few southern African sites with potentially stratified MSA and Acheulean are not known to be associated with dateable volcanic

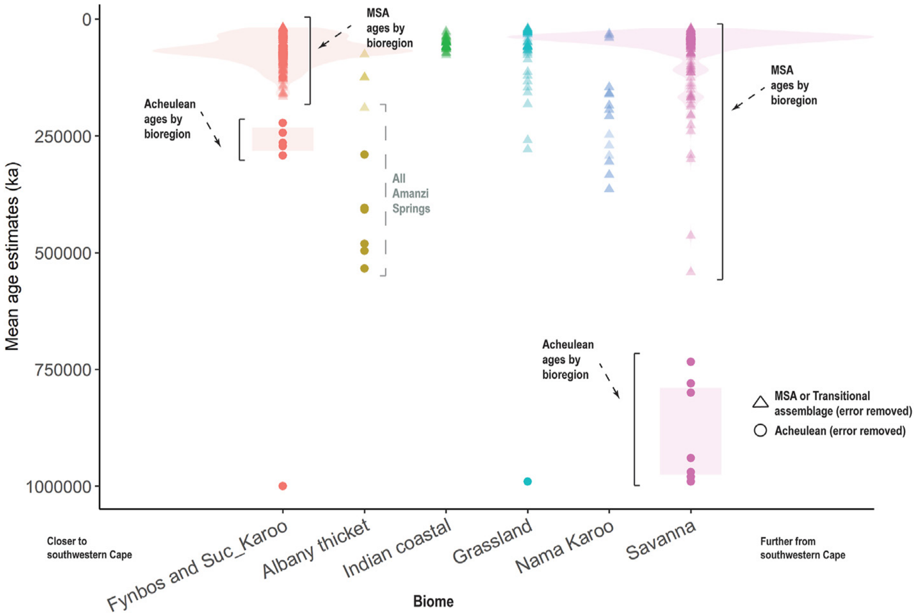

Figure 16. Distribution of published age estimates <1 Ma (error was not added to each point for readability), including biostratigraphic estimates, for Middle Stone Age (MSA) and transitional industries, as well as the small number of existing age estimates for Acheulean sites in vegetation biomes of South Africa. Data were acquired from the ROCEEH Out of Africa Database (https://www.roceeh.uni-tuebingen.de/roadweb/smarty_road_simple_search.php), selecting an age range from 50 ka to 999 ka and then extracting biome affiliation from the vegetation map in Figure 1, using functions in the Raster R package v. 3.4.5 (Hijmans et al., 2020). Violin plots (MSA) and boxplots (showing interquartile ranges for Acheulean cases) added to visualize contrast between Fynbos and Savanna biomes. For spatial references to vegetation biomes see Figure 1, though the distance of each biome from the southwestern cape broadly increases from left to right (x-axis). Note how older ages for the MSA are largely confined to the Savanna, Nama Karoo, and Grassland biomes, whereas the younger dates for the Acheulean in the Cape largely do not overlap with the MSA in this particular region.

materials, whereas radiocarbon estimates are not applicable beyond ~50 ka. This situation has resulted in much reliance on geochronologies generated through a growing variety of available luminescence techniques (Roberts et al., 2015; Penkman et al., 2022).

Several models have been developed to explain broad diachronic shifts in hominin technologies over the African Middle and Late Pleistocene. Much of this debate hinges on the tempo and nature of cultural change within and between the MSA and terminal Acheulean, on whether these changes were abrupt and progressive or random and gradual, and on how these patterns manifest in different regions of Africa. Evaluating existing explanatory models against the archaeological record relies heavily on reliable geochronologies, yet building a chrono-cultural framework for the last ~400 kyr in southern Africa—the period documenting the probable end to the Acheulean—remains challenging for geochronologists (Feathers, 2002; Herries, 2011; Herries et al., 2022).

One still highly influential view, which has been variably articulated, proposes that gradual cumulative changes in material culture through the African later Middle Pleistocene eventually resulted in uniquely modern human behavior (McBrearty and Brooks, 2000). Within this framework, the emergence of the MSA was coupled with concurrent loss of technologies assumed to be relatively more archaic such as Acheulean LCTs. This model draws substantially on data from the eastern African Rift system and is supported by environmental archives documenting increasing variability in resource availability associated with the emergence of the MSA and, perhaps more contentiously, by the proposed deep antiquity of complex technologies and ochre use in coastal South Africa (Marean et al., 2007; McBrearty and Stringer, 2007; Brooks et al., 2018). If one were to fit a model to this gradualist trajectory of cultural change, it would likely look close to logarithmic, initiating with a linear onset of innovations in the later Middle Pleistocene, but with a variable rate of change in accumulation that tapers off in the later Pleistocene. This tapering off is attributed to the suite of behaviors traditionally recognized to be modern becoming more comprehensive and archaeologically visible by ~50 ka (Henshilwood and Marean, 2003; Villa et al., 2012), although the pursuit of contemporary hunter–gather culture in the archaeological past remains contentious and regionally variable (d'Errico et al., 2012; Pargeter et al., 2016; Bader et al., 2022). In this gradualist framework, one might expect to see evidence for transitional industries with mosaics of residual Acheulean and emerging MSA technologies, such as the Fauresmith or some of the other transitional industries proposed for equatorial geographic settings (Tryon and McBrearty, 2002, 2006).

An opposing model argues that hominin capacities for culture and innovation shifted abruptly, not gradually, and that there is little clear evidence for uniquely human behavior in the archaeological record prior to the later Late Pleistocene (Klein, 2000). If one assumed the temporal pattern of change in Klein's model to be true, it may be evident now—with the availability of new dating techniques and increasing numbers of well-excavated sites—that the inflection point when material culture shifted onto a probable path toward modernity was earlier than originally suggested. Although the specific timing and causality implicated in this second model do not pertain to current discussion, the logistic pattern of temporal change potentially does. Despite reasonably widespread resistance against the relevance of Klein's model to explaining changes in the later African MSA (e.g., Scerri et al., 2018; Scerri and Will, 2023), the archaeological visibility of punctuated models of innovative change has been reasonably well established in cultural evolutionary studies (e.g., Henrich, 2001; Bettinger, 2009). The appearance of a package of complex behaviors after a period of relative stasis is a simple function of trait frequency and time, which is further influenced by the size or scale of the geographic region of focus—if one aggregates ages and archaeological data over large enough geographic regions of Africa, real punctuated changes will necessarily appear more gradual. While several nuances of the models summarized above have been suggested, most share features of inferred temporal patterning and causality, and all focus on behavioral changes internal to the MSA (Conard, 2008; Jacobs et al., 2008; Marean, 2010; Parkington, 2010).

Despite increasing numbers of ages associated with the earlier MSA in southern Africa, the pattern of temporal change between the late Acheulean and early MSA remains poorly documented, with inferences occasionally reliant on assemblages from questionable contexts. Wonderwerk Cave potentially contains Fauresmith industries deriving from Beaumont's excavations (Beaumont and Vogel, 2006; Chazan et al., 2008), though sample sizes of stone artifacts relative to volume of excavated deposit in the Acheulean and MSA layers at this site are low, which complicates drawing industrial inferences about these assemblages (Chazan, 2015; Chazan et al., 2020). In the other sites that have both stratified MSA and Acheulean layers, the change between them does not appear to be gradual and, in some instances, contains either a hiatus or limited evidence for occupation at the interface between the two (Mason, 1988; Van der Ryst, 2008), with the continuity of raw-material use between the Acheulean and early MSA at Kathu Pan potentially representing an exception (Wilkins, 2013). Some scientists have interpreted this regional pattern—more specifically an inferred disconformity at the end of the Acheulean—to be evidence for so-called population turnover in southern Africa at the time of the Acheulean to MSA transition (Marean and Assefa, 2005). This interpretation leaves open the possibility that the MSA evolved gradually from the Acheulean outside of southern Africa (or at least outside of the southwestern Cape), that populations or cultures migrated or diffused into this region from the north bringing early MSA technologies, and that these new technologies replaced local Acheulean systems.

In support of this view, Marean and Assefa (2005) asserted that one would not expect contemporaneity between late Acheulean and early MSA technologies in African regions that were relatively more marginal (less habitable) during glacial periods, and they considered southern Africa (generally) to be one such region, though more recent descriptions of potential coastal refugia ~180 km southeast of MC have also been discussed by Marean (2011). It follows that transitional industries were likely scarce and are theoretically expected in equatorial environments more favorable to human habitation during glacial periods. Assuming that the inland mountainous region of the Langeberg surrounding MC represents one such glacially less-habitable environment, this view potentially accords with the record of chrono-cultural change at MC. At MC, there is no evidence for transitional assemblages in MIS 7, shortly prior to the proliferation of the local southwestern Cape MSA, yet the site has abundant classic Acheulean technologies during this period. As yet, the site also does not appear to have hominin occupations in MIS 6, one of the coldest and driest periods of the quaternary in this region (Petit et al., 1999; Jerardino and Marean, 2010).

It is perhaps relevant that alternative explanations for abrupt shifts between Acheulean and MSA industries in southern Africa—such as nonlinear change in local industries (regardless of the underpinning mechanisms)—may look much the same archaeologically as predictions for population turnover. For instance, biased transmission of cultural innovations produces distinctly logistical uptake curves for the onset (or diffusion) of new technologies, showing a stasis-change-stasis pattern (Henrich, 2001), which has also been suggested for the emergence of several southern African later MSA industries (Mackay et al., 2014). This logistical uptake of innovations is dependent on the changing breadth of behavioral variation in a population through time, with technologies spreading after a period of relative stasis first at an increasing then a decreasing rate. If such a process partially or wholly described the proliferation of the MSA in the southwestern Cape, it would have a diachronic trajectory challenging to distinguish from a pattern underpinned by population turnover.

Data from recent fieldwork at MC—viewed relative to the archeology of the broader southwestern Cape region—do not contradict the notion of population turnover at the end of the Acheulean, but also do not obviously support it. The earliest well-documented MSA of the southwestern Cape is represented at a small number of sites dating to MIS 6—5 (Will et al., 2019), though well-contextualized data pertaining to MIS 6 industries in this region are currently confined to the site of Pinnacle Point 13B, potentially only ~70 kyr younger than the latest occupations of MC (Marean et al., 2007; Marean, 2010).

A relevant question then concerns how the regional MSA in the southwestern Cape compares to the local later Acheulean in terms of historical relatedness. One reasonable inference may be that if the early MSA was an invasive phenomenon in the southwestern Cape, one might expect some dimensions of the assemblages representing these technologies to reflect aspects of population migration. An alternative scenario is that the earliest MSA occupations of the southwestern Cape remain as yet undocumented. Interestingly though, a review of the literature summarized below suggests that several conventional indicators of mobility or mobile populations that may be implicated in migration such as tool production and curation, core reduction systems, core reduction location relative to site location, assemblage size, and raw-material procurement do not obviously support a scenario of turnover in the earliest documented MSA of the southwestern Cape.

In summary, earlier MIS 5 industries in the southwestern Cape tend to contain flake production patterns that generally vary within a hemispheric core surface organization that was hierarchical—and thus Levallois-like—in some assemblages but, more commonly, was alternating and discoidal/bifacial in others (Volman, 1981; Wurz, 2002; Schmid et al., 2016). Early MIS 5 flake production focused on locally available coarse-grained rocks that were readily available such as quartzites and occasional quartz, where isotropic quartzite is less abundant such as the South African west coast (Will, 2021). Quartzites were often reduced on-site, generating large amounts of debitage with highly variable flake morphologies, including non-retouched convergent products and occasional unstandardized elongated products, knapped with hard-hammer percussion (Porraz et al., 2013; Wurz, 2013; Will, 2021; Tribolo et al., 2022). Evidence for retouch in these earlier MIS 5 industries is negligible. Retouched tools in early MIS 5, when present, are unstandardized in size and shape. Denticulated pieces are the most common retouched form, yet were made largely on the same local rocks that were used for simple flake production and cannot be considered curated (Lombard et al., 2012; Porraz et al., 2013; Mackay et al., 2014). At first glance, this brief simplification of earlier MIS 5 industries is not a glaring material signature of populations moving into a region from elsewhere. In fact, apart from more intensive reliance on flake production—which is characteristic of the MSA relative to the Acheulean in Africa generally—the earlier MIS 5 MSA of the southwestern Cape is not overtly different from the preceding local Acheulean, if one were to remove the LCT technologies (Presnyakova et al., 2015).

Recent research at a cave in the Fynbos biome located ~18 km from MC documented relative climate stability across the Middle Pleistocene period in which MC was likely occupied by Acheulean tool-producing hominins. While regional inferences from this study would clearly be strengthened by additional archives, current interpretation is that ecological stability resulted in low plant extinction rates and correspondingly high diversity in this region today (Cowling et al., 2005; Dupont et al., 2021; Braun et al., 2023).

As discussed already, early MSA and so-called transitional industries emerged in the Grassland and Savanna biomes of southern Africa earlier than is currently known for the southwestern Cape, possibly relevantly, in Middle Pleistocene periods wherein we know there were ecological turnovers that remain poorly dated in these biomes (Chazan et al., 2008; Codron et al., 2008; Kuman et al., 2020; Chazan, 2022). The possibility that persisting low-risk, stable, resource bases potentially underpinned aspects of persisting archaic technological systems in the southwestern Cape may therefore be an explanatory scenario worth further exploration.

5. Conclusions

Here we described the context and recovery of in situ assemblages documenting the technological adaptations of hominins in the period preceding the first appearance and proliferation of modern humans in the CFR. Documenting the process and temporal trajectory of hominin adaptation in the CFR remains key to our broader understanding of the emergence of behavioral variability in our lineage. Located in the mountainous interior between the south and west coasts of South Africa, MC is well positioned to contribute new information to this endeavor. Montague Cave contains multiple, well-stratified concentrations of artifacts reflecting some of the latest Acheulean occupations of South Africa's CFR, in a period just preceding the documentation of rapidly increasing human behavioral complexity in this biome. While this ecological setting has been key to exploring the environments in which complex modern humans evolved, we know little about how populations with pre-MSA technologies were able to survive there, due largely to a paucity of localities that retain contextualized material traces of Acheulean activities, and a lack of complementary archives documenting the environments in which Middle Pleistocene hominins subsisted.

While phytolith spectrums from MC relative to modern frameworks indicate that the CFR was associated with Middle Pleistocene occupations of the cave, we cannot discount the possibility that localized shifts in the interplay between climate, rainfall seasonality, and local ecosystems could have resulted in environmental contexts that are not easily comparable to modern environments known in this region today. How Middle Pleistocene hominins adapted to their environments, whether ecological parameters influenced their technological systems and in what ways, and how variability in this interplay compares with the archaeological records of other southern African regions comprise important future research avenues. Future work should further explore the relevance of behavioral and ecological archives at MC to hominin adaptation, at a critical stage just prior to the proliferation of the local later MSA.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary Online Material

Supplementary online material to this article can be found online at https://doi.org/10.1016/j.jhevol.2023.103435.

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