Quaternary Science Reviews 253 (2021) 106763

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

The expansion of the Acheulian to the Southeastern Ethiopian Highlands: Insights from the new early Pleistocene site-complex of Melka Wakena

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A R T I C L E I N F O

Article history:
Received 22 August 2020
Received in revised form
8 December 2020
Accepted 11 December 2020
Available online 29 December 2020

Keywords:
Early stone age
Eastern africa
Acheulian
Melka wakena site-complex
Geographic expansion
Highlands occupation
Dino formation
Lithic technology
Site formation processes
early Pleistocene

A B S T R A C T

Current models of early hominin biological and cultural evolution are shaped almost entirely by the data accumulated from the East African Rift System (EARS) over the last decades. In contrast, little is known about the archaeological record from the high-elevation regions on either side of the Rift. Melka Wakena is a newly discovered site-complex on the Southeastern Ethiopian Highlands (SEH) (>2300 m above mean sea level) just east of the central sector of the Main Ethiopian Rift (MER), where eight archaeological and two paleontological localities were discovered to date. Nine archaeological horizons from three localities were tested so far, all dated to the second half of the early Pleistocene (~1.6 to >0.7 Ma). All the lithic assemblages belong to the Acheulian technocomplex. Here we report on geochronological, stratigraphic, paleontological and lithic technological aspects of the tested localities and contextualize them in the broader framework of hominin cultural evolution in eastern Africa. Findings from Melka Wakena, assessed against the backdrop of the few other highland sites (Melka Kunture and Gadeb), support a scenario of expansion rather than dispersal from the Rift to the highlands. When considered in the context of the Rift-highlands interface, results of the first-phase research at Melka Wakena help to parse existing general models into archaeologically testable hypotheses and demonstrate the site's potential to contribute to research of early prehistory and to understanding the dynamics of early Pleistocene hominin populations in eastern Africa.

1. Introduction

Current models of early hominin biological and cultural evolution are shaped almost entirely by the data accumulated from the East African Rift System (EARS) over the last half century. In contrast, little is known from the highlands on either side of the

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https://doi.org/10.1016/j.quascirev.2020.106763

EARS, which are therefore largely precluded from broad discussions of the early archaeological record in Africa. Here we introduce the results of the first phase of archaeological work at the highland site-complex of Melka Wakena (Southeastern Ethiopian Highlands; SEH), contextualize it into the broader framework of hominin cultural evolution in eastern Africa and outline its potential to inform the broader discussion.

Favorable preservation conditions, combined with an abundance of datable geological horizons, created strong incentives for a research focus on the Rift, and ensuing major discoveries drew ever-increasing attention to this geological context. Aside from unparalleled archives of hominin fossils going back to the late Miocene, archaeological localities in the Rift document the appearance of the Oldowan, the first enduring lithic technocomplex, at ~2.6 Ma, and its subsequent proliferation in time and space (Braun et al., 2019; de la Torre, 2011b; Hovers, 2012; papers in Hovers and Braun, 2009; Plummer and Finestone, 2017; Semaw, 2000). The earliest occurrences of the Acheulian technocomplex, dated to 1.75–1.7 Ma, were also documented from Konso Gardula, Olduvai Gorge and West Turkana in the Rift and rift margin sequences (Beyene et al., 2013; de la Torre and Mora, 2014; Díez-Martín et al., 2015, 2019; Lepre et al., 2011), after which the Acheulian became a geographically widespread phenomenon in the Rift, as well as within and beyond the African continent (e.g., Bar-Yosef and Goren-Inbar, 1993; Isaac and Curtis, 1974; Isaac and Isaac, 1977; Leakey, 1971; Mohib et al., 2019; Pappu et al., 2011; Petraglia et al., 2009; Shipton et al., 2014; Stanistreet et al., 2018). The shift to the Acheulian is characterized archaeologically by the addition of new and more complex lithic artifact types (known collectively as Large Cutting Tools) to the technological repertoire, by a higher diversity of the lithic assemblages, and by clearer lithic-fauna spatial and functional associations related to procurement of faunal resources. This shift is regarded as a major break from the preceding Oldowan. The emergence of the Acheulian is argued to represent higher cognitive abilities from those of Oldowan-making hominins and is suggested to mark a fundamental change in hominin lifeways (de la Torre, 2016; Gallotti and Mussi, 2018; Stout, 2018; Stout et al., 2015).

Until recently, only five early paleoanthropological sites/site-complexes were known from high elevation (hereafter “highland”) contexts (≥2000 m above mean sea level; amsl) of Ethiopia (Fig. 1a). Fanta (Lanzarone et al., 2016) and Chilga Kernet (Todd et al., 2002) were only cursorily studied and reported. Extensive work, including dating to the early Pleistocene, took place only in Melka Kunture (MK) (e.g., Chavaillon and Piperno, 2004; Gallotti and Mussi, 2015; 2017; Morgan et al., 2012; Mussi et al., 2016; Tamrat et al., 2014) and in the Gadeb site-complex (Clark, 1987; Clark and Kurashina, 1979b; Kurashina, 1978; Williams et al., 1979). (Fanta and Melka Kunture are effectively within the Rift setting, but are located on the highland as defined above). Following a reclassification of all Gadeb assemblages as Acheulian (de la Torre, 2011a), the only highland evidence for the Oldowan comes from a single locality, Garba IVE-F (~1.7 Ma) in MK (Gallotti and Mussi, 2017; Piperno et al., 2009). All other early Pleistocene assemblages in Gadeb and MK are attributed to the Acheulian technocomplex. A sixth site, Kilombe, is located in Kenya slightly south of the equator, at 1830 m amsl, at the rift-plateau escarpment. Similar to the Ethiopian sites, it is (broadly) dated to the early Pleistocene without a pre-Acheulian cultural component (Bishop, 1978; Gowlett, 1978; Gowlett et al., 2015 and references therein). The recently reported Mt. Dendi site, situated ~3000 m amsl, dates to the late middle Pleistocene (Vogelsang et al., 2018). Thus, as a result of the much more intensive research in the Rift, its chronological, environmental and cultural archives served as the basis for numerous influential models of process and rate in human biological and cultural evolution.

On current data, the Rift was the geographic origin of the Acheulian and the source region for the dispersal of Acheulian-bearing *Homo erectus* out of Africa, which took place shortly after the emergence of the Acheulian (Bar-Yosef and Belfer-Cohen, 2001; Bar-Yosef and Belmaker, 2011; Bar-Yosef and Goren-Inbar, 1993; Dennell, 2003; Martínez-Navarro et al., 2012; Pappu et al., 2011). The early appearance of the Acheulian on the Rift shoulders (presumably as part of its dispersal within Africa) follows a similar timeline to that of the first out-of-Africa dispersal. Lateral movement of hominins and fauna between the Rift and the escarpment, sometimes at the expense of movement along the Rift axis, may have been promoted due to the distribution of surface water and fluctuations of lake levels in the Rift (e.g., Cuthbert et al., 2017; Trauth et al., 2010). The links between such changes and the orbitally-forced global climate shifts are not straightforward. Indeed, it was suggested (Billingsley, 2019; Grove, 2014) that dispersals out of the source area should be expected when the region switched from a period of high climate variability to a stable environment.

The emergence of the Acheulian on the highlands and the patterning of sites in space and time were explained by three models that emphasized three different scales of mobility. Following from their analysis of raw material of the Gadeb assemblages and inferred degrees of artifact curation, Clark and Kurashina (1979b) suggested a cyclic geographic expansion of Acheulian groups from the Rift to the highlands through seasonal movements over long (>100 km) distances. Later, Clark (1987) viewed the phenomenon as *Homo erectus*' expansion and broadening of its range of exploited habitats. Mussi et al. (2016) proposed a model of yet larger-scale climate-driven behavioral patterns, where hominin occupations at elevation of 2000 m or more ceased during colder periods and recurred when climate ameliorated during the early and middle Pleistocene. This suggestion is based on the sedimentological and palynological record of Gombore II at the MK site-complex, dated ~805–700 ka (spanning Marine Isotope Stage [MIS] 20 and the mid-Pleistocene transition of MIS 19). Because they suspect that occupational gaps on the highlands are due to the inability of *Homo erectus (s.l.)* to cope with harsher environments, this model presumably pertains to earlier periods as well.

The recently discovered site-complex of Melka Wakena in the SEH, close to the eastern margin of the MER, constitutes a significant addition to the sparse early Pleistocene record of the Acheulian on the highlands. Here we report on the first phase of research at the site-complex, which provides an opportunity to revisit current models about chronological, technological and ecological context of the Acheulian on the highlands and its possible relationship with its Rift counterparts. The results that we present provide a basis for constructing additional hypotheses about these issues at the site and regional levels.

1.1. Context of the MW site-complex

Located at an elevation of 2300–2350 m amsl, the MW site-complex (7°05′30″ N, 39°16′10″ E) is situated on the floodplain of the upper Wabe river, the headwater of the Wabe Shebele drainage system (Fig. 1a). Following reports about recovery of fossil bovid skulls during commercial sand quarrying, exploratory surveys in 2013–2014 revealed the presence of prehistoric localities. To date, ten paleontological and archaeological localities have been discovered along a 2 km stretch of the western bank of the Wabe. Localities MW1, MW2 and MW5 were test-excavated in 2015–2017 (Fig. 2; Table 1). Additional localities were recognized on both the

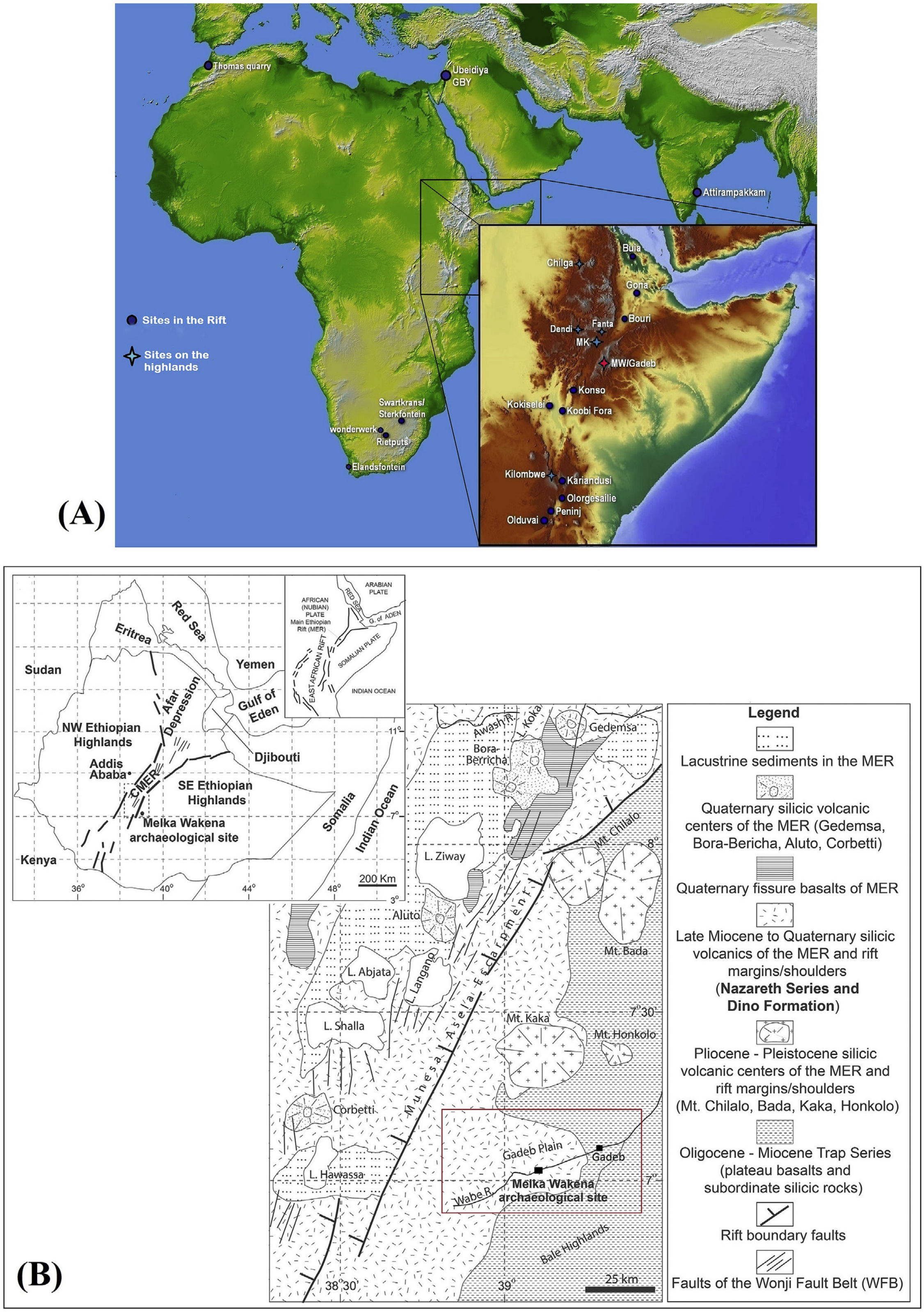


Fig. 1. (a) Location map of Acheulian sites in Africa. Inset shows eastern African sites mentioned in the text. (b) Schematic geological map of the central sector of the Main Ethiopian Rift and the eastern rift margin. Location of the Gadeb Plain is marked (modified after Resom et al., 2018).

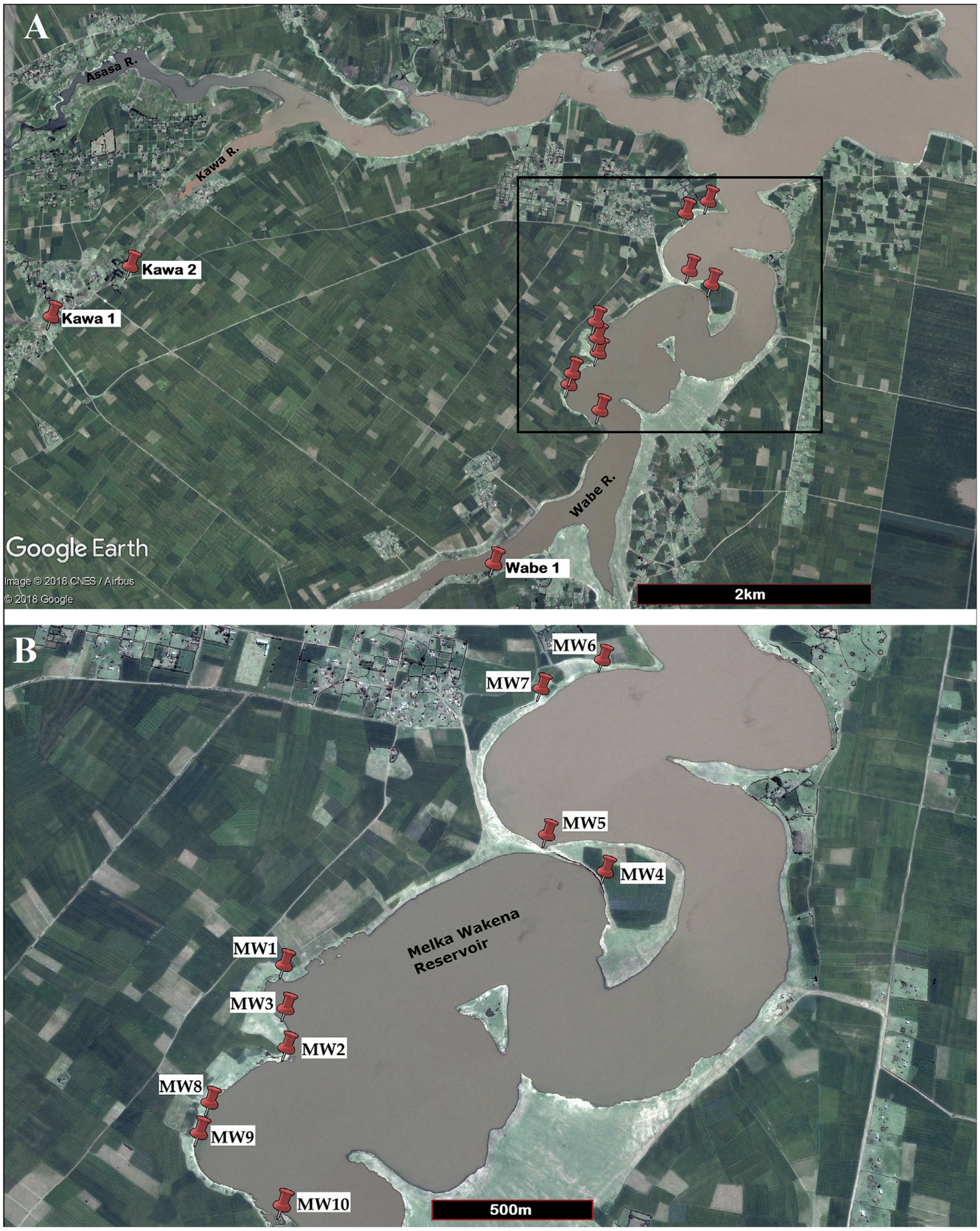


Fig. 2. (a) Location of the archaeological and paleontological localities along the meandering course of the upper reaches of Wabe River and localities on the Kawa drainage, where ignimbrite exposures were sampled (Resom et al., 2018). The marked area is shown in detail in (b).

western and eastern banks but to date these have not been explored.

The Wabe River is the headwater of the 2000 km long Wabe Shebele River (Sembroni and Molin, 2018), initially forming a shallow, wide valley as it flows to the NE on the flat plateau (referred here as the "Gadeb Plain"), before incising a >900 m deep narrow canyon across Neogene volcanic and underlying Mesozoic sedimentary rocks. On the plateau, the floodplain lays between the foothills of the Bale Mountains (>4000 m amsl) in the east and the Main Ethiopian Rift (MER) (~1700 m amsl) to the west (Fig. 1). Since the construction of the MW hydropower dam in the early 1980s, some 20 km NE of the MW site-complex, the Wabe River upstream of the dam has formed an artificial lake, with water levels fluctuating following the annual precipitation cycle as well as controlled release of water from the reservoir. As a result, the known MW localities are exposed above water only part of the year. Sites in the Gadeb research area some 8 km downstream (northeast) of MW are permanently submerged (de la Torre, 2011a).

The modern climate of the SEH is influenced by the Indian Monsoon and the nearly N–S movement of the Intertropical Convergence Zone (the African rain belt) resulting in a bimodal rainfall regime (Nicholson, 1996). Temperatures remain relatively constant throughout the year, averaging 16.9 °C in the warmest month (March) and 14.6 °C in the coldest (November). Precipitation

Table 1
MW localities.

Locality Name	Grid reference	Section of research area	Age of archaeological horizons	Description
MW1	N 7°05′00.79″ E 39°15′45.53″	Upstream	>0.696 Ma	**Excavated archaeological site**. See text.
MW2	N 7°04′51.73″ E 39°15′45.18″	Upstream	1.62–1.34 Ma	**Excavated archaeological site**. See text.
MW3	N 7°04′57.04″ E 39°15′45.19″	Upstream		**Archaeological site**. Extensive scatters of lithic artifacts, including all technological categories of knapped items, bifacial artifact, large cores and boulders, as well as diagnostic faunal remains, along ~150 m between *MW1* and *MW2*.
MW4	N 7°05′12.79″ E 39°16′15.97″	Downstream		**Archaeological site.** Situated at the neck of a peninsula on the Wabe River. The rich archaeologic and faunal finds derive from layers that are likely the lateral continuation of the horizons observed at nearby *MW5*. Excavations at *MW4* are improbable as the archaeological horizons are embedded in a steep cliff face and are overlain by more than 5-m thick sediments.
MW5	N 7°05′15.52″ E 39°16′13.04″	Downstream	1.62 Ma; 1.37–1.34 Ma	**Excavated archaeological site**. See text.
MW6	N 70 5′33.63″ E 39016′17.39″	Downstream		**Archaeological site.** Large numbers of artifacts (including bifaces and hammerstones), massive cores and boulders erode out of *in situ* sediments and are found clustered over a relatively small area. These are associated with an ignimbrite flow in the older part of the stratigraphic section (see text), which may have served as one of the sources of raw material for the knapped artifacts in the older localities (i.e., *MW5* and *MW2*).
MW7	N 7°05′32.25″ E 39°16′12.74″	Downstream		**Paleontological site.** Erosion and subsequent refilling led to re-deposition of early sediments (from the plateau above?) directly upon *in situ* Middle Pleistocene deposits. The redeposited sediments are dated biostratigraphically to the late Pliocene by a lower molar of *Elephas recki cf. brumpti.*
MW8	N 7°04′50.22″ E 39°15′42.16″	Upstream		Located in proximity to *MW2*, archaeology-bearing horizons correlate to the *MW2* archaeological sequence. In addition, a younger highly localized occurrence consists of a giant core, large flake blanks, large flakes and hammerstones, all eroding out of the section.
MW9	N 70°04′43.53″ E 39°15′35.30″	Upstream		An extensive concentration of ignimbrite boulders, giant cores, and some large flake blanks eroding out of the upper section of a sharply rising cliff. The concentration and nature of the assemblage are quite similar those observed in MW6, but only few bifaces are observed. This locality may represent a workshop for large flakes. However, stratigprahically, this locality post-dates most of the artifact-bearing Acheulian horizon with the exception of *MW1*.
MW10	N 7°04′35.92″, E 39°015′44.69″	Upstream	Upper Pleistocene	**Paleontological site**. Two nearly complete and two partial skulls of the Upper Pleistocene bovid *Synceros antiquus* were recovered in 2011 and 2012 by local sand miners, marking the beginning of interest in the site. Their presence indicates a major post-Middle Pleistocene erosion. Currently, these fossiliferous horizons lie under a 3-m thick sediment overburden that accumulated from the collapse of the bank.

occurs as rain and dew, with significant variation in monthly means ranging from 177.8 mm in August to 17.8 mm in December. While there are rainy days each month, a major summer (June–September) rainy season ("*Kiremt*") and a smaller spring (March–April) rainy season ("*Belg*") are clearly distinguished. In contrast, in the MER to the west, the mean annual, mean hottest and mean coldest temperatures are ten degrees higher, and there is a unimodal rainy season that lasts from April to September (Asrat et al., 2008; Seleshi and Zanke, 2004).

MW is located within one of the largest enclaves of the 'Afromontane Archipelago' in Africa, which consists of unique high-elevation plant communities of the tropics that are separated by low-lying areas. A characteristic of the 'archipelago' is that 'intra-island' species diversity is often greater than 'inter-island' variability, providing locally diverse vegetal landscapes. MW is located within the belt of the current Ethiopian montane grasslands and woodlands, growing at elevations of 1800–3000 m amsl (White, 1983: 165–171). In the modern environment, the transition from non-ligneous vegetation C_4- to C_3-dominated plants occurs at elevations approaching 3000 m amsl. In the area, this transition occurs on the high slopes of the central volcanoes to the north and on the Bale mountain range to the south (Figs. 1–2; and see below).

2. Materials and methods

For the sake of clarity, the methodologies used for each of the analyses conducted during this study are summarized at the beginning of each of the respective sections. The methods are reported in more detail in the Supplementary material.

3. Geology and geochronology

3.1. Geological setting

The Plio-Pleistocene geological history of the Gadeb-MW area has been associated with the evolution of the MER, which constitutes volcanic eruptions, cycles of transgressive-regressive lake levels (Eberz et al., 1988) and episodes of intensive fluvial aggradation and erosion (Resom et al., 2018). While the regional topography of the Wabe Shebele drainage basin has been relatively stable since the Oligocene (Sembroni and Molin, 2018), the most recent regional tectonic uplift affecting the SEH dates back to 4.5 Ma, after which the regional topography has been established broadly to its present configuration (Xue et al., 2018).

Between 5 and 3 Ma, the reactivation of the southern MER and counter-clockwise rotation of the Somalian plate (Bonini et al., 2005) led to voluminous silicic eruptions and extensive deposition of pyroclastic products (Corti, 2009 and references therein). Deposits of the syn-rift Nazareth Series (peralkaline pantellerite ignimbrites, rhyolite and basalt flows as well as rhyolite and trachytic domes) were laid between 5.2 and 2.6 Ma. Miocene - Pliocene felsic pyroclastic deposits of the Nazareth Series form the extensive low-lying plains of the eastern rift margin and the adjoining highland plains, including the MW study area. These plains are dotted with late Pliocene prominent volcanic shields located off-rift-axis (Corti, 2009; WoldeGabriel et al., 1990; Zanettin et al., 1978) — the volcanoes of Chilalo (3988 m amsl), Bada (4160 m amsl), Kaka (4160 m amsl) and Honkolo (3760 m amsl). The latter two are in close proximity to the MW-Gadeb Plain (Fig. 1b).

Subsequent Quaternary volcanism, associated with the oblique faulting at the active axis of the MER, took place ~1.6 Ma or later (Chernet et al., 1998; Corti, 2009; Teklemariam, 1996; WoldeGabriel et al., 1990), forming the early-middle Pleistocene Dino Formation (Kazmin and Berhe, 1981) that is exposed on both rift margins. These deposits mainly consist of pyroclastic products (ash falls and pumice) and associated volcaniclastic sediments as well as some reworked lacustrine sediments (particularly in the MER), and layers of ignimbrites (i.e., welded tuffs), trachytes, rhyolites, and rare basalt flows. Well-sorted and uniformly thick distal volcanic products in the MW area are associated with the Plio-Pleistocene activity of the large rift calderas (e.g., Aluto, Hawasa, Shalla, Bora-Bericha, Corbetti, and Gedemsa; Fig. 1b) (Resom et al., 2018). In contrast, the rhyolitic lava flows, ash flows and ash falls of proximal volcanic products (ash, pumice, pumaceous ash falls, welded tuffs) originated from the nearby large silicic central volcanoes on the eastern rift shoulder (Fig. 1b).

3.2. The Dino Formation in the MW area

Hominins in the MW area existed on a geomorphologically active and complex paleo-landscape defined by the Dino Formation. The stratigraphic and depositional setup of the area has been reconstructed from detailed stratigraphic logs from several localities of the MW site-complex (Supplementary material 1). Detailed stratigraphic logs were described at 17 well-exposed sections (Supplementary figures 1.1-1.2) along the two relatively long arcuate exposures in which the archaeological localities are found. Because of some lateral discontinuity in the stratigraphy, the logs were organized into separate Upstream and Downstream sections (Supplementary material 1; defined by Resom et al., 2018).

The stratigraphic sequence at the MW site consists of a ~30 m thick succession of pyroclastic and reworked volcaniclastic deposits and generally unconsolidated fluvial sediments (Supplementary material 1). Fluvio-lacustrine sediments are rare. The units show sharp to gradational contacts within a short vertical succession. Nearly all the units identified in the sequence are laterally discontinuous. Some units pinch out laterally at short distances (a few meters to tens of meters), while some are structurally truncated against other units.

3.3. Geochronology

A total of 377 single grain analyses of sanidine from nine volcanic deposits (Supplementary table 2.1) were analyzed by $^{40}Ar/^{39}Ar$ geochronology. These yielded results for eruption or maximum ages of volcaniclastic samples from three localities in the MW site-complex. Samples were prepared, irradiated, and analyzed in two batches (irradiation 458PRA and 469PRB). All preparation and analytical methods are provided in the Supplementary material 2. All ages of the Dino Formation volcaniclastics are calibrated according to the Alder Creek Sanidine fluence monitor (ACs, t = 1.1891 ± 0.0008 Ma, Niespolo et al., 2017; Renne et al., 2011; all Ar and age uncertainties are reported with 1σ here and throughout). All the ages fall within the regional chronostratigraphic age assigned to the Dino Formation (Kazmin and Berhe, 1981). Table 2 and Fig. 3a summarize the results.

3.3.1. Localities MW1 and MW2 (Irradiation 458PRA)

Four samples in this irradiation yielded either inferred eruption ages or maximum ages from total fusion of single grains of sanidine for Ar isotope analyses of sanidine from MW1 and MW2 localities.

Thirty-one sanidine grains from sample MW-1-G9 (altered ash fall) were measured ranging in grain size from 840 to 1200 μm. This sample yielded a multi-modal distribution of ages, indicating the presence of xenocrysts either from assimilation during eruption or post-eruptive reworking. The weighted mean age of 698.2 ± 2.5 ka (MSWD = 1.37, P = 0.22) from seven juvenile grains represents a maximum age for the deposit, consistent with field observations that this is indeed a reworked volcaniclastic deposit.

Sanidines from sample MW-2-G3 (primary ash flow) ranging from 840 to 1200 μm exhibited a homogeneous age population with only one xenocryst, thus making interpretation of this result a straightforward eruption age at 1.6225 ± 0.0039 Ma (MSWD = 1.30, P = 0.13, N = 32/33). In sample MW-2-G16 (primary ash flow) only smaller grains were present, ranging from 300 to 600 μm. Hence, the precision on individual measurements was lower than in other samples. Grains were excluded to bring the MSWD and P-value closer to 1; these are interpreted as xenocrysts and their exclusion results in a weighted mean eruption age of 1.246 ± 0.013 Ma (MSWD = 0.76, P = 0.89, N = 50/71). Two size fractions, 600–840 μm and 840–1200 μm, were measured from MW-2-G10 (reworked ash fall). Multi-modal populations and abundant xenocrysts result in a juvenile mode representing a maximum age of 1.3414 ± 0.0041 Ma (MSWD = 0.67, P = 0.83, N = 17/62). These results corroborate field observations that this deposit is likely a reworked pyroclastic/volcaniclastic sediment.

3.3.2. Locality MW5 (Irradiation 469PRB)

Four tephra deposits were sampled and dated in this irradiation from MW5 locality and one from locality MW2. Sample MW-5-G5 (primary ash fall) contained large sanidine crystals ranging from 840 μm–2 mm in size that were analyzed. There were xenocrystic modes present and a tail of older ages from some results, indicative that this sample may have been reworked or contained entrained material to include older modes. The youngest mode represents a maximum age of 1.3725 ± 0.0048 Ma (MSWD = 1.07, P = 0.37, N = 26/43). For sample MW-5-G7 (primary ash fall), grains were measured from two ranges of size fractions, 400–840 μm, and 840–1200 μm. After eliminating xenocrysts and two large grains with very young ages and small amounts of gas released (grains that were possibly not totally fused during laser heating), a distinct juvenile mode represents an eruption age at 1.2517 ± 0.0048 Ma (MSWD = 1.07, P = 0.37, N = 26/43). Grains in two size fractions were measured for sample MW-5-G9 (reworked ash fall), 400–840 μm, 840–1200 μm. A long tail of older ages derived from xenocrystic grains and two grains thought to be contaminant ACs were eliminated – the long tail of older grains indicated the youngest mode should be viewed as a maximum age of 1.3429 ± 0.015 Ma (MSWD = 0.08, P = 1.00, N – 8/41). Grains ranging from 400 to 840 μm were analyzed from sample MW-5-G2 (reworked ash fall). An older xenocrystic mode of ~2.5 Ma and additional xenocrysts were eliminated. The youngest mode defined a distinct population lacking an older tail, defining the eruption age of the deposit at 1.6266 ± 0.0064 Ma (MSWD = 0.66, P = 0.88, N = 23/32).

Sanidines in sample MW-2-G7c (lapilli ash) ranged from 400 to 840 μm in size. A homogeneous juvenile mode of 1.4451 ± 0.0193 Ma (MSWD = 0.55, P = 0.80, N = 8/22) was apparent after omitting xenocrysts and 6 grains of contaminant ACs, which may have migrated to the MW sample pit from jostling during irradiation.

The results from these two suites of samples from three localities along the Wabe River provide chronological and/or stratigraphic correlations between two of the excavated localities (MW2 and MW5) and strata that correlate with them. Table 2 provides symbols that match samples with indistinguishable eruption ages

Table 2
Summary of $^{40}Ar/^{39}Ar$ age results.

Sample ID*	BGC Lab ID	Stratigraphic unit	Mineral	N/N_0	$^{40}Ar/^{39}Ar$ Age (ka)	σ (ka)	MSWD	P-value	Age Interpretation	Possible correlates
MW-1-G9	37150	MW1- Unit III (*altered ash*)	Sanidine	7/31	698.2	2.5	1.37	0.22	Maximum age	
MW-2-G3	37148	MW2-Unit I *(primary ash flow)*	Sanidine	32/33	1622.5	3.9	1.30	0.13	Eruption age	◆
MW-2-G16	37146	MW2-Unit XIII *(primary ash flow)*	Sanidine	50/71	1246.0	13.0	0.76	0.89	Eruption age	★
MW-2-G10	37152, 37154	MW2-Unit VII (*reworked ash fall)*	Sanidine	17/62	1341.4	4.1	0.67	0.83	Maximum age	✚
MW-2-G7c	39061	MW2-Unit IV *(lapilli ash)*	Sanidine	8/22	1445.1	19.3	0.55	0.80	Eruption age	
MW-5-G5	39047	MW5-Unit III (*nearly pristine ash fall*)	Sanidine	8/42	1372.5	4.8	0.83	0.56	Maximum age	
MW-5-G7	39043, 39048	MW5-Unit VI (*primary ash fall)*	Sanidine	26/43	1251.7	4.8	1.07	0.37	Eruption age	★
MW-5-G9	39050, 39051	MW5-Unit V (*ash fall, heavily altered post-depositionally)*	Sanidine	8/41	1342.9	15.0	0.08	1.00	Maximum age	✚
MW-5-G2	39049	MW5-Unit I (*ash fall, slightly altered post-depositionally*)	Sanidine	23/32	1626.6	6.4	0.66	0.88	Eruption age	◆

within uncertainties, or that exhibit similar age distributions in samples with maximum ages. Combined with stratigraphic relations, three pairs of tephra can be interpreted as correlated: samples MW-2-G3/MW-5-G2, MW-2-G16/MW-5-G7, and MW-2-G10/MW-5-G9 (Fig. 3b). The dates of Units MW2-I and MW5-I, the lowest strata that can be currently observed in the respective localities, are identical within a single standard deviation. The reworked ash fall Units MW2-VII and MW5-V also yielded ages indistinguishable within a single standard deviation. The primary ash flow MW2-XIII is indistinguishable from the primary ash fall MW5-VI within two standard deviations. In these three cases, the juvenile modes from $^{40}Ar/^{39}Ar$ results (either interpreted as eruption or maximum ages) indicate that each pair may derive from the same eruptive event. The geochronological correlations provide a macro-scale glimpse of landscape dynamics in the MW area at three different episodes of early Pleistocene hominin occupation of the site.

4. Archaeological sequences and site formation processes

The dynamic nature of the landscape (section 3.2), with alternating phases of fluvial aggradation, erosion and refill of erosive features, affected the archaeological localities differentially, depending on their placement in relation to the fluvial paleosystem (e.g., Davies et al., 2015; de la Torre and Wehr, 2018; Díez-Martín et al., 2017; Domínguez-Rodrigo et al., 2019; Hovers et al., 2014; Marder et al., 2011; Petraglia and Potts, 1994; Schick, 1987a, b). Understanding the effects of syn- and post-depositional geogenic processes is key to understanding the anthropogenic deposits at each locality as well as at the site-complex level.

4.1. MW2

The locality was first identified due to the occurrence of artifacts and bones on the surface. A close examination of the cliff face overlooking the river revealed the presence of four *in situ* archaeological horizons (see Supplementary material 3 for field methods) numbered as layers 1–4 (L1-L4, top to bottom; Fig. 4). Archaeological Layer designations (suffixed with “L”) are independent of geological Units (roman numerals) in this and all other localities discussed in the paper.

MW2-L4 is situated at the base of Unit MW2-II and immediately above the volcanic ash of Unit MW2-I. The archaeolgoical layer was excavated over only 4 m^2, in which 8 animal bones, among them anatomical remains of large mammals (see below), were associated with 25 artifacts, all sparsely scattered at the bottom ~ 20 cm of a coarse-grained, loose sand.

MW2-L3 was identified over a distance of some 300 m along the west bank of the Wabe River. It was identified tentatively as a discontinuous exposure also along hundreds of meters on the opposite bank of the river. At the MW2 llocality, it was excavated over 13 m^2, in an area where most of the overburden had already been removed by sand quarrying. The dense concentration of lithic clasts (n = 7044, of which 6042 [86%] are anthropogenic artifacts; Fig. 5; Table 3) is associated with only 87 faunal specimens, all concentrated over a vertical distance of ~20 cm, at the contact between an underlying coarse sand (Unit MW2-II) and a fine-grained sand at the base of MW2-III. The overlying deposits of Unit MW2-III (ca. 70 cm thick) consist of a series of thin (3–5 cm thick) alternating light and dark laminae (Supplementary figure 3.1). The dark laminae contain traces of heavy metal concentrates (Resom, 2017), representing periodic (perhaps seasonal) overbank flooding and drying on an active paleo-channel. The well-sorted and upward-fining, fine sand matrix of MW2-L3 suggests low-energy sedimentation in a meandering course of a river system. Archaeological layer MW2-L4 directly overlays the top of MW2-I, dated to 1.622 Ma. Both archaeological layers are capped by Unit MW2-IV, which is dated to 1.445 Ma.

MW2-L2 and MW2-L1 are located, respectively, just above the volcanic ash Unit MW2-IV and just below volcanic ash Unit MW2-VII, and are respectively associated with the sandy Units MW2-V and MW2-VI. The sequence of sediments containing these two archaeolgical layers is constrained at the bottom and top by volcanic ash layers dated to 1.445 and 1.34 Ma, respectively (Fig. 3b). The two layers were heavily disturbed by commercial sand quarring acitvities and could not be excavated systematically. Still, surface scatters of stone artifacts were found stratigrpahically and topopgraphically above MW2-L3, and were assigned to an undifferentiated “Layer 1&2” assemblage (Supplementary material 3), clearly distinguished from the underlaying assemblages and without later assemblages in the sequence (Figs. 3 and 4). The collected artifacts are mainly fresh and unpatinated, suggesting that they have only recently been exposed on the surface. Because the artifacts (and very few faunal remains) are derived from a temporally-constrained stratigrpahic context, they can be incorporated in diachronic comparisons of techno-typological aspects of artifacts such as bifacial tools and cores (Section 6).

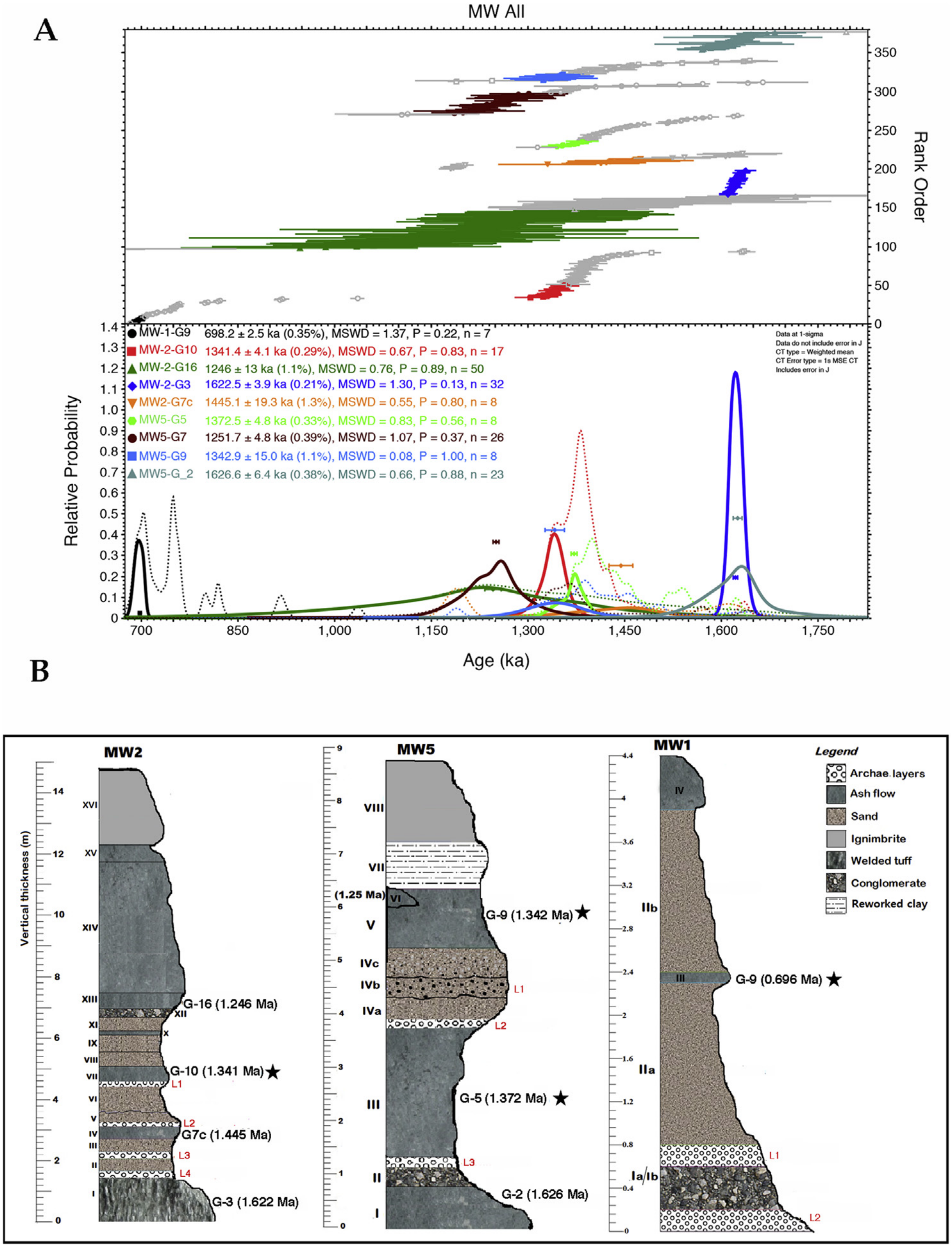


Fig. 3. (a) Weighted mean $^{40}Ar/^{39}Ar$ ages (bottom) based on probability distribution functions of single grain analyses (top). Ages calculated with the air correction after Lee et al. (2006), the ACs fluence monitor age of 1.1891 Ma (Niespolo et al., 2017) and the decay constants of Renne et al. (2011); (b) Stratigraphic sequences and radiometric dates at the three excavated MW localities. Maximum ages are marked by asterisks (see text and Table 2).

4.2. MW5

Excavations targeted an area where most of the overburden had already been removed by commercial sand quarrying in the area. Two *in situ* archaeological layers (MW5-L1 and MW5-L2, top to bottom) were recognized in an exposed cliff face (Fig. 6). The two layers are situated within a series of reworked sand, silt and volcanic ash constituting geological Unit MW5-IV. This unit, constrained by volcanic ash layers dated to 1.37 Ma (Unit MW5-III) and 1.34 Ma (Unit MW5-V) at the bottom and top, respectively, represents phases of deposition and reworking of a single sediment package, confined to a time span of ~30 ka (Table 2 and Figs. 3 and 6; Supplementary figure 3.2). The majority of the archaeological artifacts and bones derive from MW5-L2, at the bottom of a sand unit (Unit MW5-IVa). Layer MW5-L1 is a fluvial sand deposit within Unit MW5-IVb (Fig. 7, Supplementary figures 3.3-3.4).

A stratigraphically older archaeological horizon (MW5-L3) was observed on the (temporary) shoreline, above a conglomeratic unit (Unit MW5-II), which in turn rests on top of the 1.626 Ma old volcanic ash Unit MW5-I. MW5-L3 is stratigraphically some 2.5 m below the occupation horizons located on the cliff face (Fig. 3b). Small-scale excavations were conducted to expose the layer and verify its anthropogenic nature. This material is not included in the present study beyond description of its chrono-stratigraphic position (Sections 3.2, 3.3).

The ~50 cm-thick sub-Unit MW5-IVa consists of loose and well-sorted coarse sand within a fine sand matrix. The thickness of this unit varies laterally and it pinches out along the cliff face, indicating that this overbank sequence was exposed to post-depositional truncation by a fluvial system. MW5-L2 contains lithic clasts

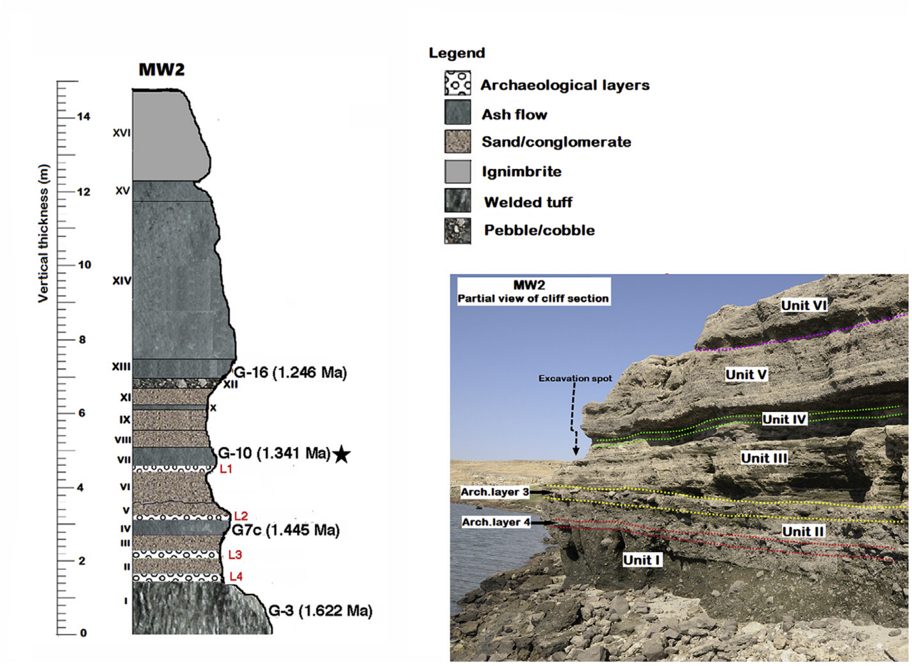


Fig. 4. (a) Stratigraphic sequence at MW2; (b) View of the cliff face showing the geological sequence. Note that the excavated area itself is not shown in this view (marked in the center of the photo).

(n = 2068, of which 1611 [78%] are artifacts; Table 3) and animal bones (n = 198). This layer has two facies (MW5-L2a and MW5-L2b). In the northern part of the excavated area, a 10 cm-thick *in situ* horizon (MW5-L2b, Fig. 7c) consists of items laying flatly directly on top of the volcanic ash (Unit MW5-III). The lithics include fresh and angular artifacts ranging in size between 5 and 30 cm, in association with faunal remains. In the southern part of the excavated area (MW5-L2a), the sediments of Unit MW5-IVa appear as a winnowed and mixed deposit, 20 cm thick, in lateral contact with MW5-L2b. While infrequent in facies MW5-L2b, in MW5-L2a cobbles co-occur with the large items. Artifacts and bones are rarely found in flat positions. This facies (MW5-L2a; Fig. 7b) is sparser compared to the *in situ* one (Table 3).

The field evidence suggests that the channel that had deposited Unit MW5-IVa was replaced by another channel, both constituting part of a large river system (Supplementary material 1). The relatively high-energy of the later paleo-channel is inferred from the size variability, degree of abrasion, and the number of natural clasts in Unit MW5-IVb. In the excavated area, the activity of this channel is seen as the reworking and displacement of anthropogenic items and bones of the *in situ* facies of the horizon (MW5-L2b) and their re-deposition as a different facies (MW5-L2a) (Fig. 7).

MW5-L1, embedded in Unit MW5-IVb (Supplementary Figures 3.2, 3.4), consists of lithic clasts (n = 512, of which 406 [79.2%] are artifacts) and bones (n = 8) (Table 3), dispersed within a 30 cm-thick mixed deposit of reworked ash, gravels and pebbles in a coarse sand matrix. In this layer the natural clasts consist exclusively of pebbles, whereas sub-rounded to angular, 2–20 cm diameter clasts (of mainly ignimbrites), are anthropogenic items.

4.3. MW1

Locality MW1 was first recognized as a distinct ledge of cemented conglomerate bearing artifacts (Figs. 8–9). Two distinct artifact horizons were observed, separated by fine conglomerate (pebble size) and cemented clasts in a matrix of coarse sand and fine conglomerate (MW1-L1 and MW1-L2; Fig. 8c). Due to receding water levels in 2015, at least two *in situ* archaeological horizons associated with conglomerates were seen eroding out of the section. Stratigraphic and lateral contacts between the new exposures and the ledge were disrupted due to prior commercial sand quarrying and related development of small channels (Fig. 8a). An extensive scatter of eroded artifacts, which cannot be linked to any specific *in situ* horizon, was observed on the re-exposed shore (these are not discussed any further).

A step trench was excavated ~50 m north of the ledge (Fig. 8; Supplementary material 3). Two archaeological layers, separated by a ~50 cm-thick sterile conglomerate, were encountered at 1 m and 1.5 m below the surface, respectively. Each horizon is associated with a coarse conglomerate (Fig. 9b) constituting pebbles and cobbles measuring 2–10 cm across. Because we were not able to fully establish continuity from MW1-L1 and MW1-L2, these horizons were designated as Step 3 [S3] and Step 4 (S4).

When water levels were unusually low during the 2016 field season, stratigraphically lower archaeological layers were observed *in situ*, also associated with coarse conglomerates. These were not tested and are not part of the following description.

The size range of the artifacts is similar across archaeological horizons MW1-L1 and MW1-L2 and MW1-S3 and -S4 (Fig. 9a and b), and tends to be larger than the pebbles that constitute the conglomerates. This suggests that the deposition of conglomerate and artifacts should be allocated to discrete geogenic and anthropogenic agents, respectively. Moreover, in both locations the flat position of the majority of artifacts (Figs. 8–9) is inconsistent with deposition by high-energy streams. The relatively high rates of abrasion of artifacts (compared to assemblages from the other localities) testify to post-depositional influence of low energy water flows that affected the preservation of artifacts discarded by hominins.

MW1-L1, the topmost visible archaeological horizon in the conglomerate ledge (Fig. 8c) is separated from the volcanic ash dated to 0.696 Ma (Unit MW1-III) by a 1.6 m thick sand (Unit MW1-

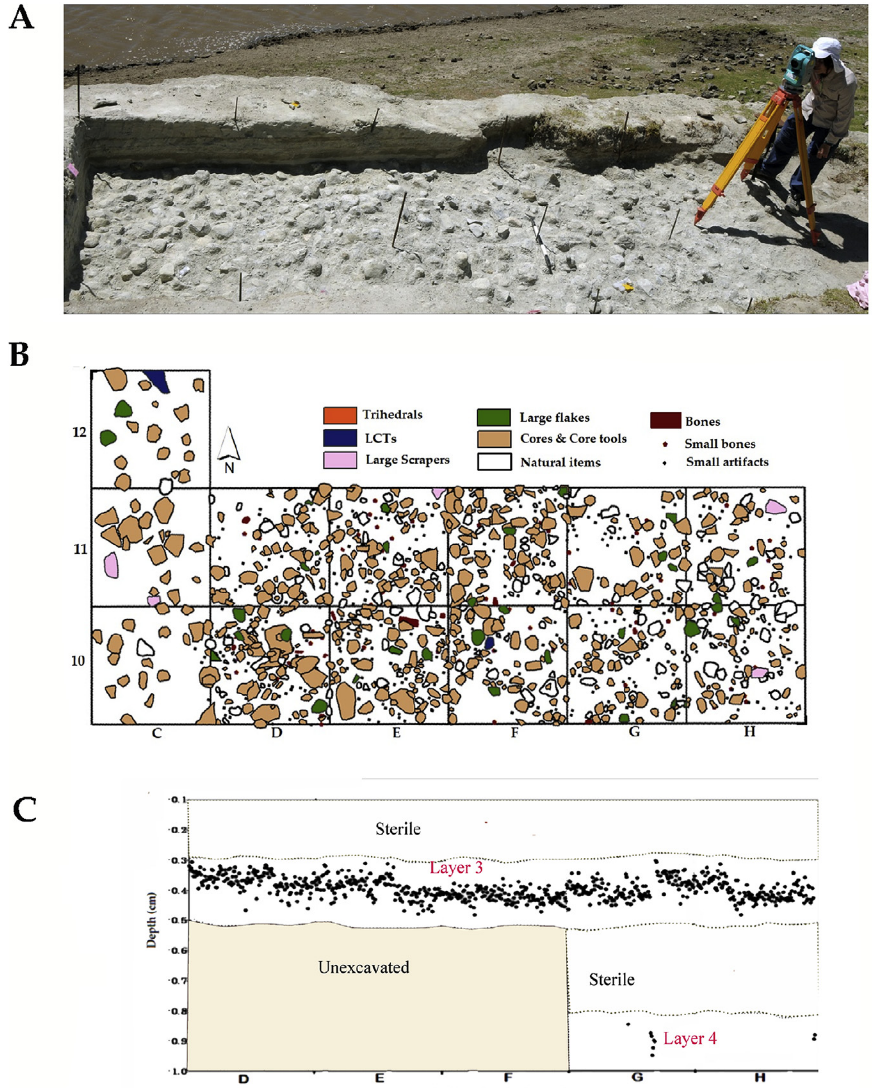


Fig. 5. (a) MW2-L3 during excavation in 2016 (view to the south); (b) Georeferenced distribution map**;** (c) plot of the vertical distribution of artifacts and bones in MW2-L3 and MW2-L4 (only piece-plotted items).

Table 3
Artifact densities in the excavated MW localities.

Archaeological layer	Excavated area (m^2)	Average thickness (m)	Excavated volume (m^3)	N of artifacts[a]	Artifact density (N/m^3)[a]
MW2-L3	12	0.2	2.40	6402	2667.5
MW5-L1	10	0.2	3.00	406	135.3
MW5-L2a	5.5	0.2	1.10	905	822.7
MW5-L2b	4.5	0.1	0.45	706	1568.9
MW1-S3	2.3	0.3	0.69	136	197.1
MW1-S4	1.5	0.3	0.45	219	486.7

[a] Natural clasts and indeterminate items excluded from density calculatiosn.

IIa; Table 2; Fig. 8b). While there are not enough dated layers to estimate the rates of deposition in this locality, the rate of deposition from the well-constrained sand in the nearby locality MW5 (Unit MW5-IV) indicates that an average deposition rate of the sand layers in the area can be approximated to ~0.5 mm/year. Considering local variations in depositional and erosional processes, we estimate the likely upper age of MW1-L1 to be ~0.8 Ma.

5. Paleontology

The faunal assemblage from the MW site-complex is not large. Most of the faunal elements were found *in situ* during systematic excavation at the archaeological localities, where they were collected and documented using the regular excavation protocols (Supplementary material 3). Some fossils were found in outcrops along the banks of the Wabe River and their location documented

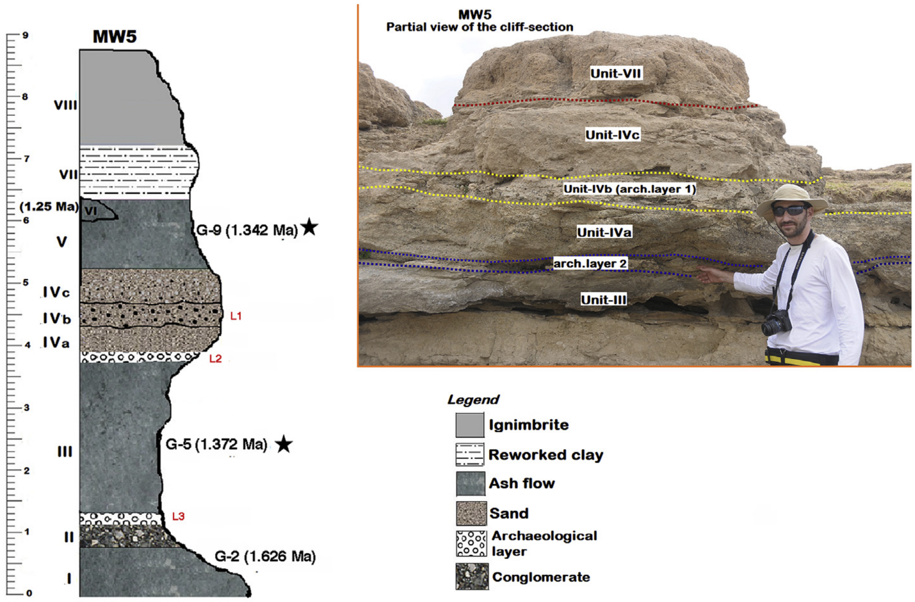


Fig. 6. (a) Stratigraphic sequence at the MW5 locality; (b) A view of the cliff face showing archaeological layers 1 and 2 in their geological context.

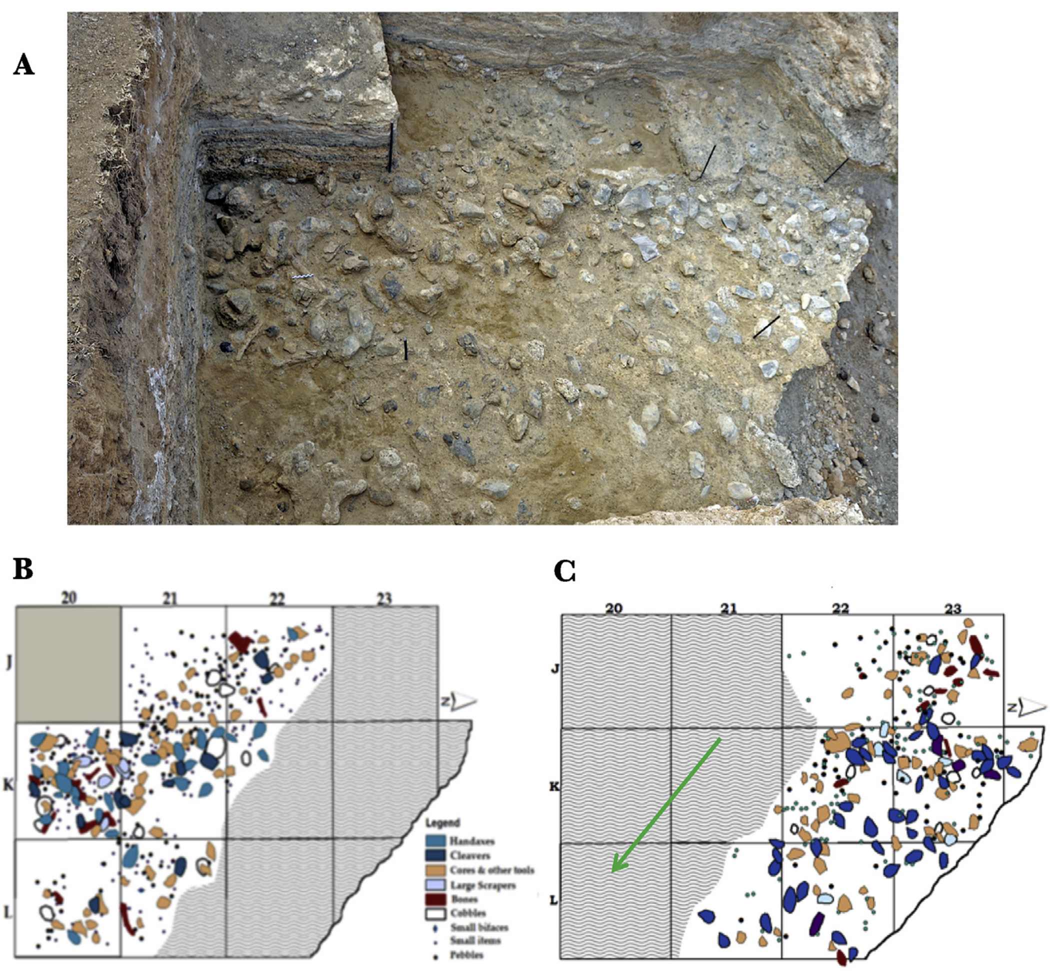


Fig. 7. (a) MW5-L2 during excavation in 2017 (view to the west); (b) Georeferenced distribution map of piece-plotted items, showing the disturbed facies (MW5-L2a); (c) Georeferenced distribution map of piece-plotted items, showing the *in situ* facies (MW5-L2b). The shaded area in (c) represents a significantly reworked part of Layer 2. The arrow shows the reconstructed direction of the channel that reworked and translocated artifacts from the *in situ* area.

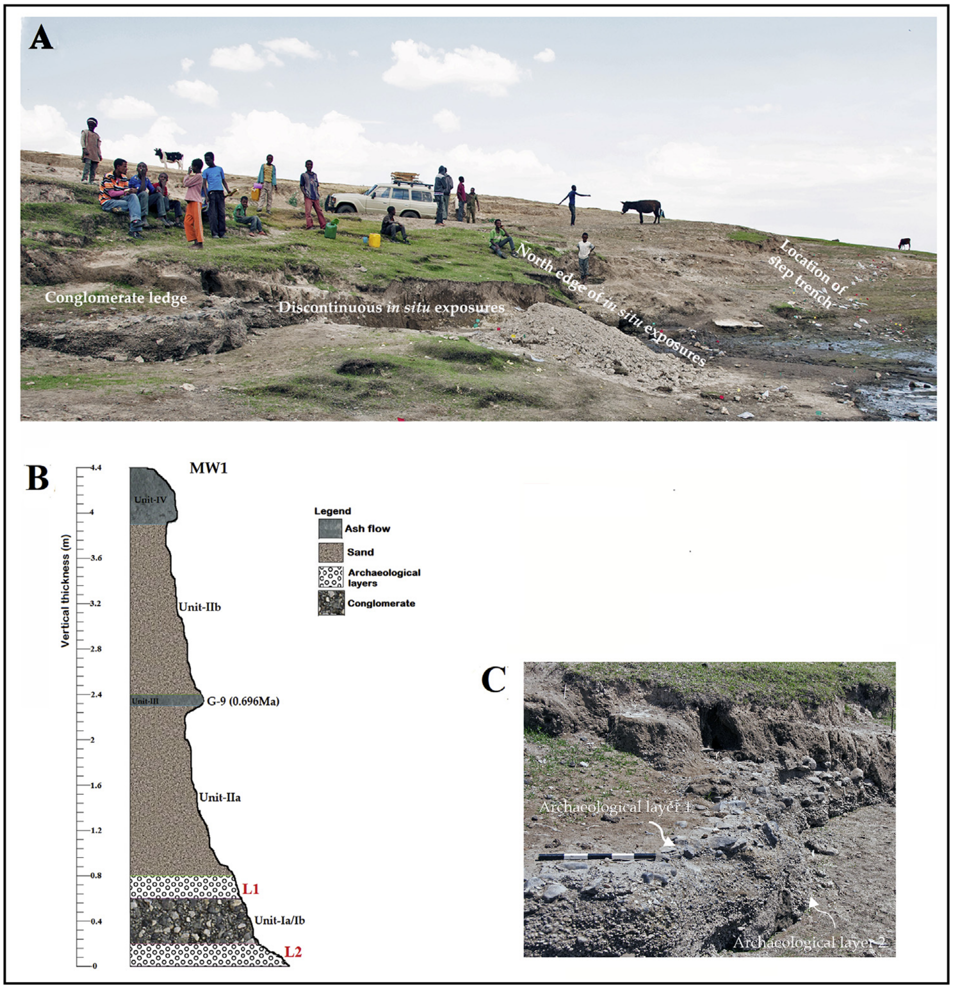


Fig. 8. (a) General view of MW1, including part of the surface scatter, with color flags marking locations of eroded artifacts (Yellow for cleavers/large flakes, red for bifaces, green for cores and hammerstones. The locations of a handful of bones from this collection are not seen in this view); (b) Stratigraphy at the MW1 locality; (c) The conglomerate ledge exposed at the southern edge of the collapsed mass of sediment. Note the two identifiable archaeological layers (MW1-L1 and L2). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

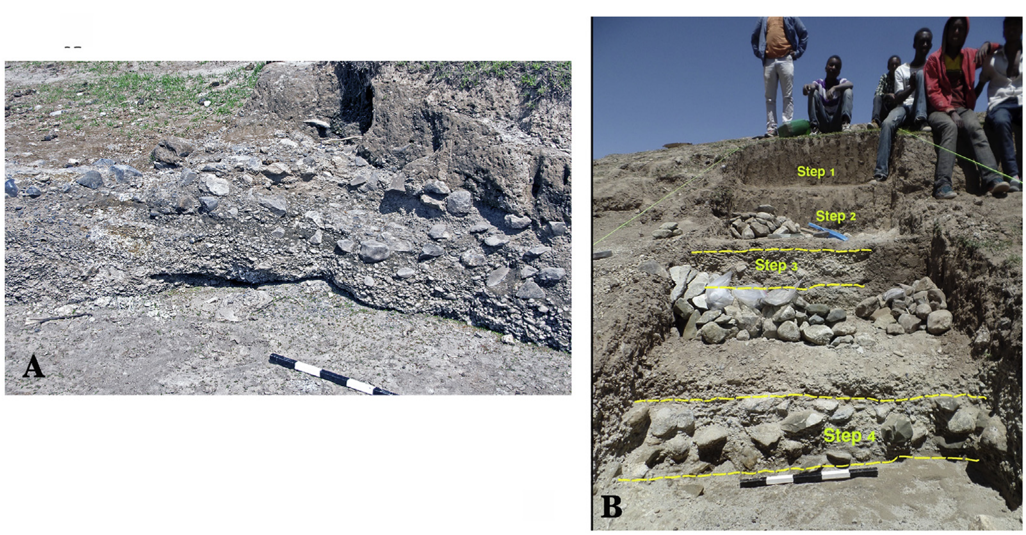


Fig. 9. (a) The conglomerate ledge at MW1. The large artifacts are lying flatly on top of a small-clast conglomerate. Two artifact horizons (right; MW1-L1 and MW1-L2, top to bottom) are separated by a sand-gravel conglomerate that pinches out to the north (right); (b) Step trench at the MW1 locality. In this view only the artifacts in Step 4 are seen *in situ*. Note the similarity to the conglomerate ledge in size and composition of the clasts. Artifacts piled on top of Step 4 are those already removed during excavation.

using handheld GPS. Only a few fossils were collected out of stratigraphic context (Supplementary material 4). Most of the finds could be correlated stratigraphically to excavated archaeological horizons or to the broader geological stratigraphic framework. Although some of the fossil vertebrates found within archaeological contexts are well preserved, the majority are fragmented, with bone cortical surface partly or totally destroyed.

The composite list of taxonomically identifiable fauna consists of 15 species of large vertebrates (Table 4), some of which are aquatic (*Crocodylus* cf. *niloticus)* or prefer aquatic environments (*Hippopotamus gorgops,* Reduncini indet.) and thick vegetation (*Tragelaphus* sp.), whereas others are savanna/open woodland species (*Equus* sp., *Metridiochoerus modestus, Giraffa* cf. *jumae, Aepyceros* cf. *melampus,* Bovini indet. (cf. *Pelorovis* sp.), *Gazella* sp., Alcelaphini indet). The list also includes *Canis* sp., *Elephas recki* cf. *brumpti, Reduncini indet.* and Antelopini indet.

A single elephant tooth was found in locality MW7, which is stratigraphically younger than the Acheulian localities. However, it belongs to *Elephas recki* cf. *brumpti*, a primitive Pliocene form. The tooth was reworked fluvially into deposits younger than 1.3 Ma, but we are as yet unable to identify potential Pliocene exposures from which this specimen may have reached the Dino Formation sequence at MW. All the other fauna in the small assemblage from the site are biochronologically consistent with faunal assemblages from the second half of the early Pleistocene in eastern Africa (Supplementary material 4).

The fragmentary state of most of the faunal specimens from excavation and their poor preservation hamper taphonomic observations. To date, cut marks, gnawing marks, teeth punctures or other indications of taphonomic agents have not been identified on any of the faunal specimens. Two hippo long bones from MW2-L4 may have been fractured by stone-assisted percussion when fresh (Fig. 10).

6. The lithic assemblages

The methodology of attribute analysis was used in this study to quantify the distributions of traits pertaining to physical preservation, flaking technology and morphological typology of the lithic artifacts, and their patterning within and between assemblages (Supplementary material 5). Data are compiled from Gossa (2020). MW2-L4 is excluded from the following analyses, unless otherwise specified, due to its small sample size. Similarly, the surface collected material from MW2-L1&L2 is excluded from analyses focusing on assemblage structure. Since it is well-constrained chrono-stratigraphically within the MW2 locality sequence, it is used in comparative diachronic analysis of select types (e.g., the Large Cutting Tools, LCTs). In all the other cases, protocols of retrieval and curation were identical (Supplementary material 3; and see below), and retrieval biases cannot be evoked to explain inter-assemblage differences. Our aim here is to present some important trends along the MW sequence. The detailed lithic analyses will be published elsewhere.

The same artifact categories occur in all the assemblages (Table 5; Fig. 11a). There is an increase in the frequencies of LCTs from the older (MW2-L3; 0.1%, n = 6) to younger assemblages (15.5% and 9.6% in MW1-S4 and MW1-S3, respectively), as well as in frequencies of LCT-related flakes and of percussive items (hammerstones, anvils, battered blocks and split cobbles that are probably broken hammerstones).

The changes in the frequencies of artifact categories co-occur with the disappearance of microartifacts from MW1 assemblages, while in the earlier assemblages they account for 30%–40% of the total assemblage. Because LCT thinning and finishing activities should have led to higher frequencies of microartifacts, the absence of the latter from MW1 assemblages, combined with the conglomeratic context, suggests fluvial winnowing (e.g., Dibble et al., 1997; Hovers et al., 2014; Malinsky-Buller et al., 2011; Petraglia and Potts, 1994; Schick, 1987a, b). High frequencies of abraded items in MW1 compared to the other assemblages support this interpretation (*cores*: 71% and 55.3% in S3 and S4, respectively, compared to 24.8% in MW2-L3 and 18.8% in MW5 samples; *debitage*: 35% and 41% compared to 10.5% and 2.1%; *LCTs*: 40% and 38%, compared to none in the MW2-L3 and MW5 assemblages; Gossa, 2020). Whether the increase in LCT frequencies is a result of these geogenic processes or it represents a real increase in the focus on LCT production remains an open question.

Percussive objects account for only a small fraction of the elements in any of the assemblages. They are typically made on cobbles of dense and heavy rocks, likely retrieved from the local channels. In MW2-L3, 13 out of 25 objects (52%) are made on basalt, as are all four items in MW2-L1&L2. In MW1-S3 five of seven items (71.4%) are made on basalt. In MW1-S4, hammerstones are made mostly of phonolite (five of seven items, 71.4%).

Two lithic production systems were identified in all the assemblages (Fig. 11a). One is a system geared toward the production of small and medium sized (2–10 cm) flakes, represented by cores, core trimming elements (CTE) and flakes. Items associated with this production system are made on a variety of raw materials (Fig. 12a), procured as cobbles from local channels.

Table 4
Faunal taxa identified in MW localities[a].

	MW5-Unit II	MW2-L4	MW2-L3	MW8	MW3	MW6	MW5-L2b	MW5-L2a	MW5-L1	MW4	MW1	MW7
Crocodylus* cf. *niloticus									X	X		
***Hystrix* sp.**											X	
***Canis* sp.**	X											
Elephas recki* cf. *brumpti												X
***Equus* sp.**				X			X	X		X		
Metridiochoerus modestus	X						X					
Hippopotamus gorgops		X	X			X	X			X		
Giraffa* cf. *jumae			X									
***Tragelaphus* sp.**							X					
Bovini indet. (cf. *Pelorovis* sp.)								X				
***Aepycerus* cf. melampus**							X	X	X	X		
***Gazella* sp.**										X		
Alcelaphini indet.					X							
Reduncini indet.										X		
Antelopini indet.							X		X			

See Supplementary Material 3 for a complete list, including specimens outside the defined localities.
[a] Localities are ordered from oldest to youngest (left to right) based on available dates and stratigraphic relationships (assumed for MW6).

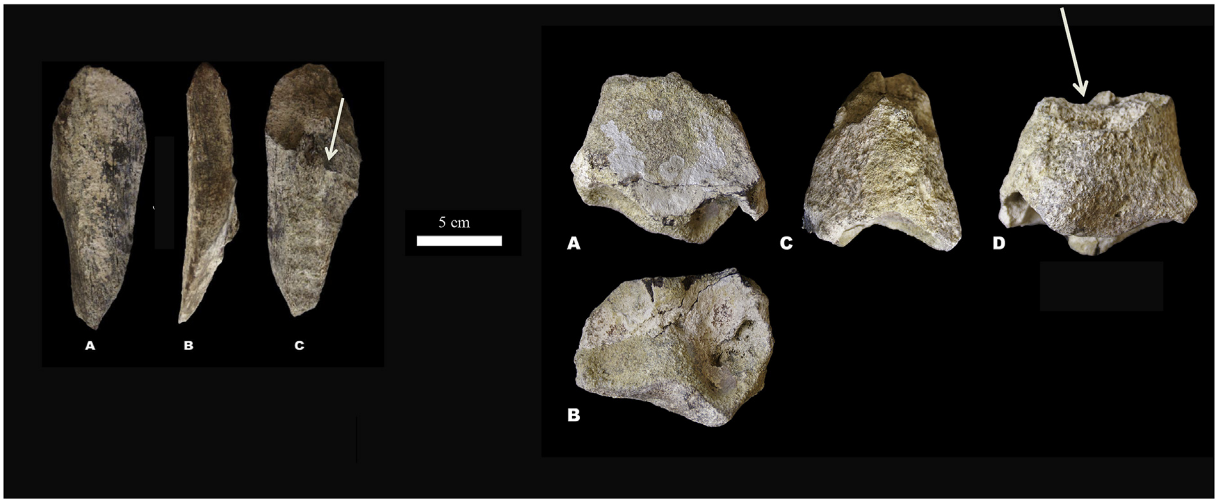
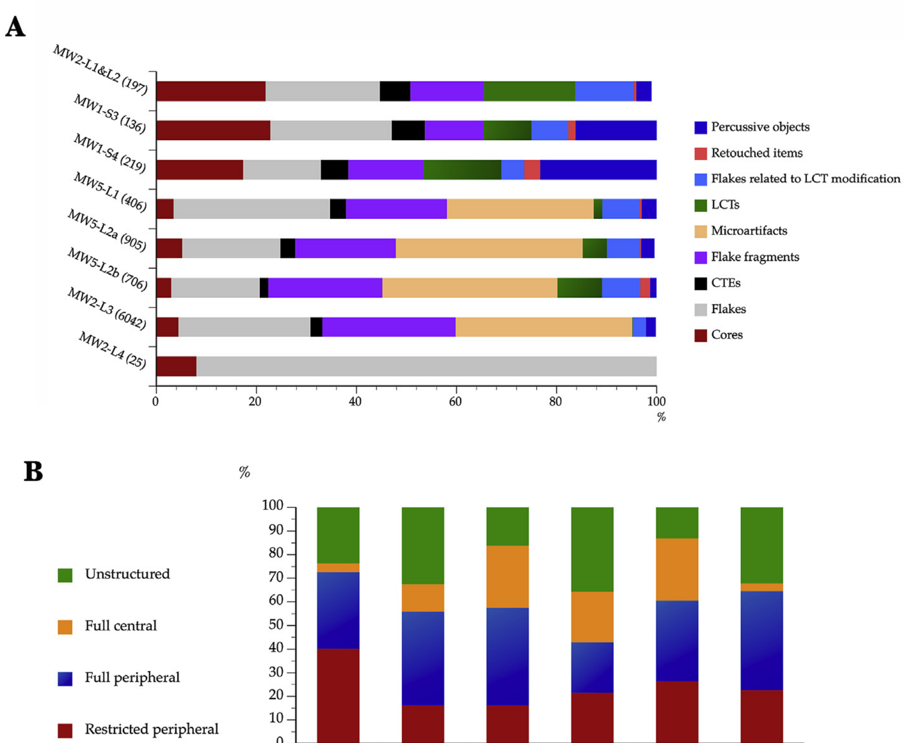


Fig. 10. Bones with anthropogenic modifications; Left: #MW2-B929, medial tibia fragment of *Hippopotamus gorgops*, percussed; Right: #MW2-B878, distal right tibia of *Hippopotamus gorgops*, percussed. Arrows indicate the notched areas.

Table 5
Composition of the MW lithic assemblages (*Percentage in ***total artifacts;*** **Percentage in ***category;*** ***Percentage in ***total assemblage***).

	MW2-L4		MW2-L3		MW2-L1&L2		MW5-L2b		MW5-L2a		MW5-L1		MW1-S4		MW1-S3	
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Cores*	**2**	**8.00**	**266**	**4.40**	**43**	**21.83**	**21**	**2.97**	**47**	**5.19**	**14**	**3.47**	**38**	**17.35**	**31**	**22.79**
Debitage (all)*	**23**	**92.00**	**5642**	**93.38**	**111**	**56.35**	**599**	**84.84**	**784**	**86.63**	**371**	**91.38**	**89**	**40.64**	**58**	**42.65**
*LCT related (all)**&*	-	-	*160 (2.83)*	-	*25 (22.52)*	-	*54 (9.02)*	-	*60 (7.65)*	-	*30 (8.09)*	-	*10 (1.12)*	-	*10 (17.24)*	-
*Core modification related (all)**&*	*3 (13.04)*	-	*144 (2.55)*	-	*12 (10.81)*	-	*12 (2.00)*	-	*27 (3.44)*	-	*13 (3.50)*	-	*12 (13.48)*	-	*9 (15.52)*	-
*Flakes (>20 mm)***	*16 (69.57)*	-	*1595 (28.27)*	-	*45 (40.54)*	-	*125 (20.87)*	-	*177 (22.58)*	-	*127 (34.23)*	-	*34 (38.20)*	-	*33 (56.89)*	-
*Angular flake fragments (>20 mm)***	*3 (13.04)*	-	*1610 (28.54)*	-	*29 (26.13)*	-	*161 (26.88)*	-	*182 (23.21)*	-	*82 (22.10)*	-	*33 (37.08)*	-	*16 (27.59)*	-
*Microartifacts (<20 mm)***	*1 (4.35)*	-	*2133 (37.81)*	-	-	-	*247 (41.24)*	-	*338 (43.11)*	-	*119 (32.08)*	-	-	-	-	-
LCT (all)*	**-**	**-**	**6**	**0.10**	**36**	**18.27**	**63**	**8.92**	**44**	**4.86**	**7**	**1.72**	**34**	**15.53**	**13**	**9.56**
*Handaxes/preforms***	-	-	*4 (66.67)*	-	*29 (80.56)*	-	*52 (82.54)*	-	*36 (81.82)*	-	*7 (100.00)*	-	*29 (85.29)*	-	*13 (100.00)*	-
*Cleavers***	-	-	-	-	*1 (2.78)*	-	*11 (17.46)*	-	*8 (18.18)*	-	-	-	*5 (14.71)*	-	-	-
*Picks***	-	-	*2 (33.33)*	-	*6 (16.67)*	-	-	-	-	-	-	-	-	-	-	-
Retouched items (all)*	**-**	**-**	**10**	**0.17**	**1**	**0.51**	**14**	**1.98**	**6**	**0.66**	**2**	**0.49**	**7**	**3.20**	**2**	**1.47**
*Large scrapers***	-	-	*6 (60.00)*	-	-	-	*9 (64.29)*	-	*2 (33.33)*	-	*1 (50.00)*	-	*7 (100.00)*	-	-	-
*Retouched Tools (All)***	-	-	*4 (40.00*	-	*1 (100.00)*	-	*5 (35.71)*	-	*4 (66.67)*	-	*1 (50.00*	-	-	-	*2 (100.00)*	-
Percussive objects (all)*	-	-	**118**	**1.95**	**6**	**3.04**	**9**	**1.28**	**24**	**2.65**	**12**	**2.96**	**51**	**23.29**	**32**	**23.53**
Hammerstones**	-	-	*25 (21.19)*	-	*4 (66.67)*	-		-	-	-	*1 (8.33)*	-	*(13.73)*	-	*7 (21.88)*	-
Anvils**	-	-	*13 (11.107)*	-	-	-	-	-	-	-	-	-	-	-	-	-
Modified Battered Blocks**	-	-	*37 (31.36)*	-	-	-	-	-	-	-	-	-	-	-	-	-
Modified Items**	-	-	*43 (36.44)*	-	*1 (16.67)*	-	*9 (100.0)*	-	*24 (100.00)*	-	*11 (91.67)*	-	*40 (78.43)*	-	*25 (78.13)*	-
Split Cobbles**	-	-	-	-	*1 (16.670*	-	-	-	-	-	-	-	*4 (7.84)*		-	-
Total artifacts	*25*	*100.0*	*6042*	*100.0*	*197*	*100.0*	*706*	*100.0*	*905*	*100.0*	*4066*	*100.0*	*219*	*100.0*	*136*	*100.0*
% artifacts***	***100.0***		***85.70***		***97.50***		***82.80***		***74.40***		***79.30***		***89.80***		***94.40***	
Natural items***	**-**	**-**	**91**	**1.30**	**-**	**-**	**108**	**12.70**	**231**	**19.00**	**79**	**15.40**	**14**	**5.70**	**-**	**-**
Indeterminate***	**-**	**-**	**914**	**13.00**	**5**	**2.50**	**38**	**4.50**	**80**	**6.60**	**27**	**5.30**	**11**	**4.50**	**8**	**5.60**
ASSEMBLAGE TOTAL	**25**		**7047**		**202**		**852**		**1216**		**512**		**244**		**144**	

Note: Three additional handaxes were recovered from surface at MW5.
& CTE – all flakes that are related to the preparation and exploitation of cores (shoulder flakes, wedges etc). LCT-related flakes include roughout flakes, thinning flakes and finishing flakes, as defined by e.g., Goren-Inbar et al., (2018) and references therein. All the flakes in these two categories are larger >20 mm.



	MW2-L3 (266)	MW2-L1&L2 (43)	MW5-L2 (68)	MW5-L1 (14)	MW1-S4 (38)	MW1-S3 (31)
Restricted peripheral	40.23	16.28	16.18	21.43	26.32	22.58
Full peripheral	32.33	39.53	41.18	21.43	34.21	41.94
Full central	3.76	11.63	26.47	21.43	26.32	3.23
Unstructured	23.68	32.56	16.17	35.71	13.16	32.26

Fig. 11. (a) Composition of lithic assemblages from *in situ* contexts (note that although not visible in this view, 6 LCTs are present in the MW2-L3 assemblage, constituting 0.1% of the artifacts); (b) Distribution of core categories in MW assemblages (see text and Supplementary material 5 for additional details and definitions).

For the Gadeb assemblages, de la Torre (2011a and references therein) suggested a core classification system where various combinations of technological traits – the number of knapped surfaces and the extent of exploitation of the central area of the exploited surface – describe the organization of core reduction and how it impacts the duration of core use life (see Supplementary material 5; Supplementary figure 5.1). Variations of bifacial knapping methods were the most frequently applied to cores in the small-to-medium flake production system within MW assemblages (Fig. 13c). The frequencies of such bifacially flaked cores increases with time (MW2-L3, 52.7% [n = 140]; MW2-L1&L2, 53.5% [n = 23]; MW5-L1&L2 combined, 70.7% [n = 58]; MW1-S4&S3 combined, 59.7% [n = 41]; Gossa, 2020). In addition, from ~1.4 Ma onward core use lives were extended by increased emphasis on full rotation to economize the use of core striking platforms and of the central area of the knapped surface, augmenting exploitation of raw material mass (Fig. 11b; Supplementary material 5). Goals of the reduction sequence do not seem to have shifted (Gossa, 2020), and frequencies of secondary modification by retouch remain marginal (Fig. 11a), suggesting that the amount of cutting edge, rather than specific forms, was the desired end-product.

A second production system, geared toward the making and maintenance of LCTs (Fig. 11a), is represented by large flakes (>10 cm), LCTs (picks, handaxes and cleavers) and flakes related to LCT shaping (i.e., roughing-out, thinning and finishing flakes; defined after Goren-Inbar et al., 2018; Goren-Inbar and Sharon, 2006; Newcomer, 1971) (Fig. 13d–i). The production of LCTs in all MW assemblages reflects a strong selection for large flakes (>10 cm; Supplementary material 5) made of massive ("glassy") ignimbrite (Fig. 12a), as opposed to the assortment of raw materials that characterize the production system for small-medium flakes. Glassy ignimbrite also dominates the category of late-stage LCT shaping (thinning and finishing) flakes (Gossa, 2020). Large and giant cores (following the definition of Sharon, 2009), from which large flakes could be removed, occur infrequently in any of the assemblages (Fig. 13a and b), suggesting that blanks were brought into the localities by the hominins, and then were shaped into bifacial tools. Cores made on glassy ignimbrite cobbles from the local streams are sometimes found in the assemblages, but they are few and are smaller in size than the large ignimbrite flakes (Gossa, 2020).

Diachronic changes in the LCT production system are more dynamic than those observed in the flake reduction system. Picks only occur in assemblages of locality MW2, from 1.6 Ma to ~1.4 Ma, after which they disappear from the site's record. While cleavers are made exclusively on flakes, MW1 assemblages show an increase in the frequencies of handaxes made on cobbles (13.7% [n = 4] in MW1-S3 and 23.4% [n = 3] in MW1-S4, compared to 3.4% [n = 3] in MW5-L2 and none in the other *in situ* assemblages). For all types of LCTs, side-struck and special side-struck flakes were preferred

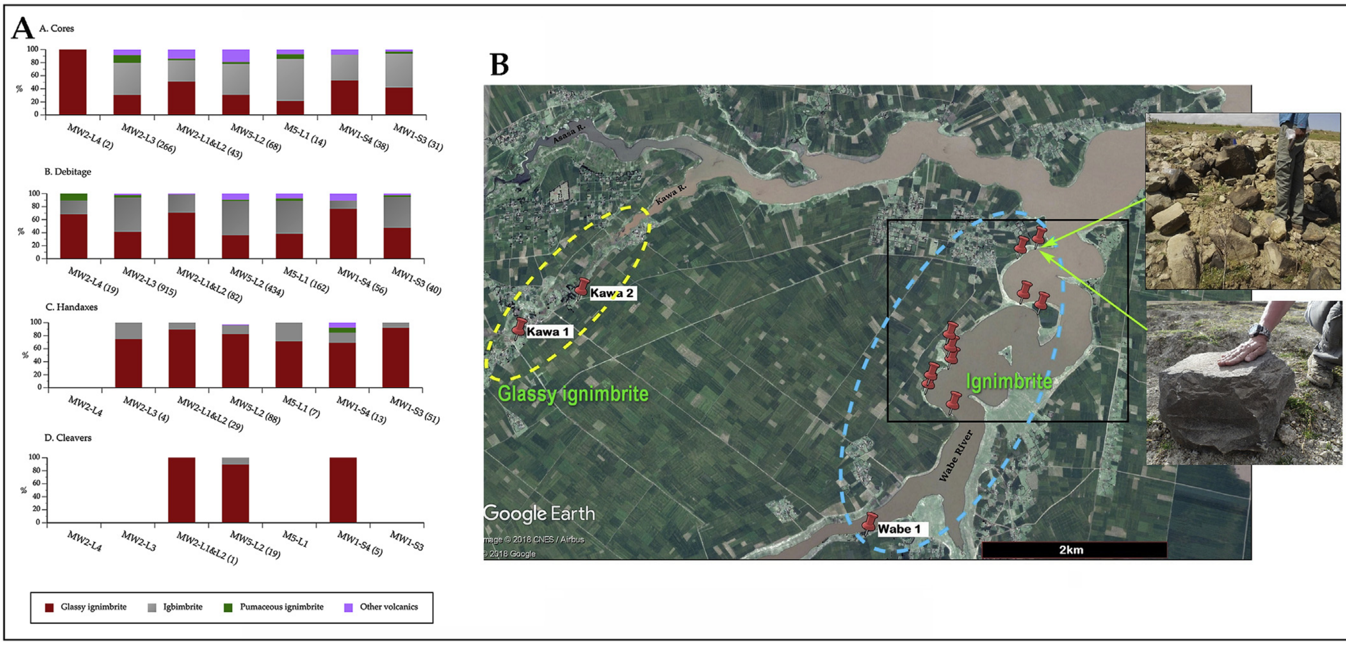


Fig. 12. (a) Distribution of raw materials in the artifact categories from *in situ* archaeological contexts; (b) Location of modern-day exposures of glassy ignimbrite (left) and strongly welded tuff (ignimbrite) (right) in the vicinity of the MW localities. Inset: views of the ignimbrite flow and giant core at MW6. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

through time, with a first appearance of Kombewa flakes at ~1.4 Ma (see Supplementary material 5 for flake type definitions).

There is an overall temporal trend for increasing investment in the shaping of both faces of handaxes and cleavers, expressed in higher scar numbers (Supplementary figure 5.2) and more complex scar patterns (Gossa, 2020), to the degree that shaping obliterated the characteristics of the blanks, i.e., whether they had been flakes or cobbles. This is reflected in the high frequencies of "indeterminate" blanks in the young MW1 assemblages. The higher intensity of shaping did not affect the overall sizes or the relative length of the working edge (Gossa, 2020), but seems to be related to increased emphasis on shape standardization.

7. Discussion

7.1. The MW site-complex

7.1.1. Landscape evolution and paleogeography

Early Pleistocene paleoanthropological sites on the highlands are poorly known in the archives of eastern Africa. This may be due to real past differences in the distribution and density of prehistoric occupations on the highlands compared to the Rift. Alternatively, it may be a result of research bias or of objective obstacles (e.g., low visibility due to more soil development and higher vegetation cover; poor preservation in populated, intensively cultivated areas; poor conditions for accumulation and/or preservation due to the geological and geomorphological factors which favored erosional over depositional processes; or a combination of all of the above). Be that as it may, the paucity of research of this time period outside of the Rift has shaped the prevalent view of human origins within the discipline of paleoanthropology and constrained our ability to address specific questions about the early occupation of the highlands as well as broader issues of pattern, pace and process in cultural and biological aspects of human evolution.

Against this background, the initial results of work at the MW site-complex add important new data conducive to advancing the discussion of such issues. Work at the site recorded a series of archaeological localities, of which a few, located along the western bank of the Wabe River, were tested. The observed sequence is dated to the second half of the early Pleistocene, from 1.6 Ma to ~0.8 Ma. Notably, the earlier part of the site's stratigraphic sequence is presently under water, and the exposed sequence may not document the earliest anthropogenic deposits in the area.

The pre-existing topography, formed and modified by tectonic processes, played an important role in determining the spatial distribution and thickness of the pyroclastic and fluvial deposits on the Gadeb Plain (similar to MK; e.g., Kusák et al., 2016; Maerker et al., 2019). At the MW site, the gentle and rolling topography formed by the extensive, mostly pyroclastic sequences of the Mio-Pliocene Nazareth Series acted as an erosional base for the sand and cobbles accumulated in the low-lying paleo-depressions close to the Wabe River channel. In addition, many of the streams that start from the northern slopes of the Bale mountain range transported sediments (conglomerates, sand and silt) to these depressions. Repetitive episodes of explosive volcanism in the nearby MER and of the rift shoulder central volcanoes led to the deposition of primary pyroclastic ash falls and flows in between fluvial sedimentation, reworking of volcaniclastic materials, as well as episodes of erosion of different intensities. Such repetitive volcanic and sedimentary processes are well recorded mainly in the later part of the geo-archaeological sequence of the Downstream localities. The sequential aggradation and erosion in fluvial environments have been the pre-requisite for favorable preservation of the archaeological record.

The available evidence suggests that during the time span of the early Pleistocene to the early middle Pleistocene the Gadeb Plain was a hydrologically active area. Reduced channel energy when the drainages debouched from the slopes of the Bale mountains onto the plain led to the formation of a dense network of channels and streams, at places depositing fining-upward conglomerate-sand sequences by meandering rivers. In addition, diatomite deposits reported from the Upstream section of the MW site suggest the

Fig. 13. Examples of lithic artifacts from MW archaeological horizons: (A) LCT core from MW2-L3; (B) LCT core from MW5-L2; (C) Discoidal core from MW5-L2; (D) Pick from MW2-L1&L2; (E) 'Atypical' biface (or preform) from MW2-L3; (F) Handaxe from MW5-L1; (G) Small handaxe from MW5-L2; (H) 'typical' handaxe from MW1; (I) Cleaver from MW1. Raw materials: A-C were made of ignimbrite, while D-I were made on glassy ignimbrite. Note the different size scales of the cores and LCTs.

formation of temporary ponds or ox-bow lakes (Resom et al., 2018), and sediments at the nearby Gadeb area suggest the presence of a late Pliocene/Plio-Pleistocene lake (Williams et al., 1979). Some of the primary pyroclastic materials were reworked, transported and redeposited as volcaniclastic sediments.

This scenario is corroborated by the dated samples. The alternation of eruption and maximum ages along the depositional series (Section 3.3) shows that fluvial processes and subsequent depositional events occurred in context of active volcanic and hydrological processes. Consistent with this broad perspective of the region, the stratigraphic profiles at the archaeological localities themselves (Section 4; Supplementary figures 3.1-3.2) indicate that all hominin occupations are associated with fluvial contexts, either drying-flooding cycles of channel beds (MW2-L4 and MW2-L3) on proximal floodplains of a large, low-energy drainage, or associated with higher-energy channels transporting both cobbles and pebbles (MW5-L2b and MW5-L1, MW1). The lithic assemblages themselves reflect the different channel regimes. The paucity of microartifacts in MW2 and MW5 assemblages, and their absence from MW1 assemblages, are likely related to different levels of winnowing by streams. At MW1, the lack of microartifacts coincides with higher levels of abrasion of the anthropogenic items (Section 6) and with higher frequencies of natural pebbles and cobbles (Table 5). Taken together, these data suggest changes in the nature of the fluvial depositional contexts that imply higher channel energies in the later assemblages compared to earlier ones.

The magnitude of erosion and redeposition in the channels is higher in the Downstream section of the MW site. As the Gadeb Plain has been tectonically stable at least since the late Pliocene (Sembroni and Molin, 2018; Xue et al., 2018), such changes in channel activity could be related to local erosional processes influenced by increased stream action, which becomes more apparent since ~1.3 Ma. This in turn could be associated with a progressively drying climate which favored open grasslands (see below).

At the site of MK, on the western margin of the MER some 200 km to the north, tree and shrub taxa belonging to the dry evergreen Afromontane forest/grassland complex were established ~1.8 Ma ago and dominate (~80%) the pollen assemblages of the early Pleistocene from 1.8 Ma (Bonnefille et al., 2018). Changes in the composition of the community and in species abundances occurred at intervals of tens of thousands of years. At the time of the early Acheulian ~1.6 Ma, the MK landscape shifted from more woody vegetation to extensive mountain grasslands (found today above the forest zone). Bonnefille et al. (2018) linked the temporal change in pollen abundances to orbitally-forced climatic events and suggested that the expansion of the grasslands occurred during cool and dry climate conditions (see also (Bonnefille, 1976; Bonnefille et al., 1982). At the same time, they noted broadly synchronous variation over small spatial scales, where true juniper woodland occurred as patches within the grassland vegetation associated with the early Acheulian sites. While pollen spectra from MW are currently unavailable, the fact that the MW and MK sites mirror each other on either side of the MER, and their location within similar regional climatic regimes, could imply the vegetation landscapes at both sites were similar within the variability of the Afromontane vegetation 'islands' (White, 1983; cf. Kingdon 1989; Mairal et al., 2017).

The MW faunal assemblages, albeit small, provide corroborating evidence for spatio-temporal variability during the time of Acheulian presence on the Gadeb Plain. Fully aquatic, water-dependent, and open woodland/grassland animals are present in the faunal collections of MW2-L4, MW2-L3 and MW5-L3 (dated roughly ~1.6 Ma) and from MW5-L2 and MW5-L1 (~1.4—1.3 Ma). Species diversity is similar but abundances and evenness vary. In faunal assemblages dated to the later time span, open landscape species are more frequent at the expense of water-dependent animals. If this pattern holds with larger sample sizes, it might correspond to a period of drier climate at ~1.4—1.3 Ma, potentially associated with the onset of higher erosion rates in the Downstream part of the MW site (Section 3.2; Supplementary Figure 1.2). Alternatively, higher channel energy could have caused hominins to distance their occupations from the main stream, thus biasing the structure of the faunal community in the sites' vicinity toward open-landscape species (see below).

7.1.2. Organization of the lithic technological system

All the lithic assemblages excavated to date from the MW localities belong to the Acheulian technocomplex. Although handaxes and cleavers are missing from the assemblages of MW2-L3, the Acheulian small debitage system is represented by structured cores (Section 6; Fig. 11). A few large flake/preforms (a technological hallmark of the Acheulian (de la Torre and Mora, 2005; Gowlett, 1986; Kleindienst, 1962; Leakey, 1971; Sharon, 2007) and few large cores indicate the use of a system of large flake production. LCT manufacture/maintenance is attested by the presence of LCT-related flakes, few picks, and a small number of large cores (Fig. 11a). This is a combination of properties that defines early Acheulian assemblages in Africa and the Levant (Bar-Yosef and Goren-Inbar, 1993; Beyene et al., 2015; de la Torre and Mora, 2020; Gallotti, 2013). Here we concur with the notion that the Acheulian technology can be recognized even if LCTs (in the classical sense) are not present (de la Torre and Mora, 2020) and consider the assemblage of MW2-L3 to be Acheulian, similar to Garba IVD (Gallotti, 2013) and the earlier assemblages reported from Konso and West Turkana (see below). The increased frequencies of LCTs and their by-products in assemblages post-dating MW2-L3 underscore the affiliation with the Acheulian technocomplex.

The technological systems for small debitage, for large flake production and for LCT maintenance continue to occur in tandem throughout the MW archaeological sequence. The small flake production system shows a tendency for increased core exploitation through time, achieved by using diverse combinations of core rotation and surface exploitation (Fig. 11b). In similarly-dated assemblages in Africa, the use of full rotation and central surface exploitation were suggested to indicate a higher degree of pre-planning and of control over flake size and shape of the resultant flakes (e.g., de la Torre et al., 2003; 2008). In MW, however, there is no significant decrease in the variability of flake morphometric properties (e.g., dimensions, plan shape or cross-sections; Gossa, 2020). While it is possible that MW hominins did not diversify their technological behavior due to cognitive impediments that reduced or prevented their control over flake morphometric variability, a more parsimonious hypothesis is that the shift to exhaustive flaking modes in the MW assemblages is related to raw material economizing. This is supported by the quantitatively marginal frequencies of retouch on the small-medium flakes throughout the site's sequence, suggesting that the small debitage reduction system was not geared toward obtaining control over flake shape or size by either knapping or modification.

The production system of LCTs exhibits a mix of technological conservatism combined with typological and technological changes. Raw material selection (strongly focused on glassy ignimbrite) is highly conservative through time. The same is true of blank selection, as most picks and handaxes and all the cleavers were made on large side-struck flakes. Glassy ignimbrite, which forms during rapid cooling and welding of a pyroclastic flow, is dense and heavy and when broken exhibits sharp edges. It appears in extensive exposures at some distance from the site (Section 7.1.3), where it is characterized by big phenocrysts of alkali feldspar (from <1 mm up to 8 mm in size) within a glassy matrix as well as minor quartz crystals visible both in hand specimens and in thin sections (Resom, 2017). Sharon (2008) showed that Acheulian toolmakers could produce LCTs from a variety of relatively coarse-grained raw materials, depending on their availability at the right size and quality. The glassy ignimbrite was brought to MW as finished or semi-finished blanks, the latter being sometimes shaped on the spot. It therefore seems that the technological decision-making of the MW LCT makes knappers involved the optimization of the quality and size of the raw material in relation to transport distance (see section 7.1.3).

A notable typological change is the disappearance of picks from the MW record after ~1.4 Ma (Table 5). Another change is the increasing investment in the shaping of bifacial tools (Section 6; Gossa, 2020; Gossa et al., 2018). This investment is emphasized especially in the MW1 assemblages, in which the frequency of cobble-based handaxes is higher than in earlier assemblages. Still they do not differ in their values of relative thickness and elongation, proxies for refinement, from the flake-based LCTs, due to more intensive shaping flake removals. This in turn suggests that the initial selection of cobble blanks focused on the larger clasts in the local drainages for the extended shaping process to be applied.

7.1.3. Land-use

The chronological sequence at the MW site indicates that the area was attractive for hominin occupation over a period of several thousand years between 1.6 Ma and ~0.8 Ma. Occupation was presumably interrupted when volcanic ash falls occurred (see also Altamura et al., 2020). The excavated localities constitute narrow windows into the nature of the landscape and the spatial extent of hominin activities in the area. In addition, large-scale erosion during the latter part of this time span disrupted the lateral distribution of the archaeology-bearing deposits. The earlier deposits are more continuous laterally.

Archaeological layer MW2-L3 extends laterally over more than 300 m along the western bank of the Wabe River and correlates with the oldest archaeology-bearing deposit at MW5, some 750 m to the northeast (Figs. 2b and 3b). A similar archaeological layer, similarly overlaying a unit of welded tuff, was identified also on the eastern bank of the river, where it outcrops discontinuously along several hundred meters. This distribution suggests that at least by ~1.6 Ma, the MW area was pervasively occupied by hominins. Arguing from parsimony, these (and possibly other similarly located sites, e.g., the Gadeb localities, some 8 km downstream from MW and dated 1.48–0.78 Ma), would be multiple occupations across the landscape. While it is unlikely that all these occupations were synchronous, this extensive distribution of Acheulian remains illustrates the appeal of the region for hominin groups, in broad agreement with Clark's (1987) model of highland occupation (discussed below).

Notwithstanding the currently small areas of excavations, the archaeological layers provide some clues about the land-use behaviors of hominins across the landscape of the Gadeb Plain. The observed selection of raw material for the various tools and products of the technological systems (Fig. 12a) implies exploitation of the landscape at different spatial scales and different levels of investment in production and transport. Percussive tools were obtained locally as pebbles and cobbles from the channels, as was the case also for a fraction of the MW1 handaxes. The strongly welded tuff (ignimbrite) used for the production of large flakes is exposed today in the vicinity of the archaeological localities as flows that disintegrate into big boulders (Fig. 12b). At MW6 (Fig. 2b) the flow is intercalated into the site's stratigraphy and likely was available to hominins as a source of raw material. The giant boulder cores (Fig. 12b), debitage and bifaces observed at the exposed flow suggest that it was used as a workshop. In contrast, large boulder cores are rare in the localities themselves, which suggests that large ignimbrite flakes were mostly brought to the localities in semi-finished or finished state. The process of large flake production can be considered to have been spatially fragmented, because the products of its initial and final stages were found in locations separated by tens to up to hundreds of meters. This could reflect attempts to reduce energetic costs, even at this short distance.

The use of glassy ignimbrite, which is not available locally at the MW site area, involved longer transport distances. Today, the closest exposures are along the Kawa River, 4–5 km west of the MW site-complex (Figs. 2b and 12b). This is consistent with the occurrence of this raw material mainly as late-stage debitage (thinning and finishing flakes) and as LCTs at the MW localities. In the Gadeb sites, Clark and Kurashina (1979b) observed the same pattern for a small number of glassy ignimbrite flake-based handaxes. They noted the presence of ignimbrite exposures some 8 km west and south of Gadeb (presumably the exposure at the Kawa River, or its lateral extension), from which either blanks or finished items were transported to Gadeb. Thus, on-site and off-site data from the MW and Gadeb sites allow a partial reconstruction (based as it is on a single type of resource) of the ranges of mobility and exploitation territories of the Acheulian tool-makers on the Gadeb Plain.

The faunal remains from MW2 and MW5 are less informative about the question of land-use. Hominin involvement in the formation of the faunal assemblages is implied by two instances of percussed hippo bone in MW2-L4 (Fig. 10; Supplementary material 4). The depositional context of MW2-L4 suggests the immediate proximity of a large water body, supporting an argument that body parts of these large animals were not transported over a large distance from where the animal was procured. Hippo remains found in MW5 may have been moved over a slightly longer distance, given the depositional context of the archaeological material. More speculative argumentation for hominin agency derives from the absence of carnivore remains from the faunal assemblages associated with the cultural material (Table 4), which is common in Acheulian assemblages (Martinez-Navarro, 2018). However, because the frequency of terrestrial carnivores on the landscape is expected to be lower than that of herbivores, the effect of the small sample size cannot be ruled out. This is also the reason that transport decisions cannot at this time be inferred from zooarchaeological studies of these assemblages.

7.2. MW in a broader context

The earliest Acheulian localities in Konso Gardula (KG), Olduvai and West Turkana (WT) date to ~1.75–1.7 Ma (Beyene et al., 2013; Chevrier, 2012; Díez-Martín et al., 2015; Diez-Martín et al., 2019; Lepre et al., 2011). A series of sites dated to ~1.6 Ma: KGA4-A2 (KG; Beyene et al., 2013), Kokiselei 5 (WT; Roche et al., 2003; Texier et al., 2006), BSN-12 (Gona; Quade et al., 2004; Semaw et al., 2018) and possibly Lepolosi (Diez-Martín et al., 2014a; Luque et al., 2009) are contemporaneous with MW2-L4, MW2-L3 and MW5-L3. Many more sites are known from the time range of ~1.5 Ma to ~0.78 Ma. These include localities in KG (Beyene et al. 2013, 2015), Middle and Upper Bed II at Olduvai Gorge (e.g., de la Torre and Mora, 2005; 2018; 2020; Díez-Martín et al., 2014b; McHenry et al., 2016; Stanistreet et al., 2018), Okote member at Koobi Fora (Feibel et al., 2009; Isaac and Harris, 1997; McDougall and Brown, 2006), localities in the Daka member of the Middle Awash (de Heinzlein et al., 2000; Schick and Toth, 2017), Buia (Abbate et al., 1998; Martini et al., 2004), ST Complex in Peninj (de la Torre et al., 2003, 2008; Domínguez-Rodrigo et al., 2002; Mora et al., 2003) and Olorgesailie (Behrensmeyer et al., 2002; Deino and Potts, 1990; Isaac and Isaac, 1977).

None of the localities known from the highlands are coeval with the earliest Acheulian localities in the Rift. The sequence of Acheulian occupations at MW is broadly contemporaneous with a number of Rift sites dated ~1.6 Ma to 0.8 Ma and with the MK localities (~1.5 Ma to 0.8 Ma; Gallotti, 2013; Gallotti et al., 2010; Gallotti and Mussi, 2017; Gallotti et al., 2014), Gadeb (Clark and Kurashina, 1979a; de la Torre, 2011a; Eberz et al., 1988; Kurashina, 1987; Williams et al., 1979) and Kilombe (with only bracketing ages, <1.9 Ma and 0.78 Ma; Bishop, 1978; Gowlett, 1978; Gowlett et al., 2015). Thus, the temporal relationship between the Rift and the highlands suggests that the former was the source region for the Acheulian (which possibly emerged during periods of high climate variability; e.g., Maslin et al., 2014; Potts, 1998, 2013), from which it reached the highlands. Ongoing work on tephra geochemistry would allow narrower comparisons and possibly cross-referencing of dates between the highlands and the Rift, resulting in a better understanding of the suggested spatio-temporal dynamics of the Acheulian.

Models of early hominin biological and cultural evolution in the Rift increasingly link evolutionary changes with the effects of climate variability (i.e., secular oscillating variations) as opposed to change (a directional trend towards different climatic conditions) (e.g., Kingston et al., 2007; Maslin, 2017; Potts, 1998; 2012; 2013; Trauth et al., 2010; Trauth et al., 2007). Grove (2014) noted that climatic variability can lead to long-term maintenance of behavioral plasticity. He suggests that a specialized population would respond to climate instability by *expanding* geographically to fill its natal area and contiguous areas, to which it is best adapted. For a less-specialized population (i.e., with higher plasticity), a better solution could be to forego competition in the natal area by *dispersing* and relocating to other, possibly discontinuous areas where it can apply flexible, possibly innovative, solutions. The model also suggests that greater levels of plasticity tend to evolve in response to higher climate variability; when a period of low instability follows a rapid transition from high to low climate variability, dispersals are likely to occur during the low-variability period (Grove, 2014 and discussion therein; also see Billingsley, 2019).

While the difference between climate change and climate variability may also be one of scale (i.e. what appears as a directional trend may be a segment of a longer-term variability if viewed from a longer temporal perspective), it is a useful distinction (Grove, 2014). In such a framework, it is of interest to consider which of the two processes led to the arrival of Acheulian-bearing hominins on the highlands, taking into account that the highland sites of MW, Gadeb and MK (and possibly Kilombe) fall within a period of globally low climate variability (1.694 Ma − 1.116 Ma [Potts, 2012: Fig. 4; and Supplementary table 2.2]. Under a scenario of dispersal, behavioral innovations (albeit not overall cultural turnover) should be expected to emerge on the highlands as solutions to novel problems of a new environment, and would be expected to be seen in the archaeological record.

In a detailed review of lithic data from Acheulian assemblages in eastern Africa, Gallotti (2013; Gallotti and Mussi, 2017) pointed out the pervasive co-occurrence of production systems for small debitage and for LCT in the assemblages. Predictably, given the extensive temporal and geographic dimensions they reviewed, inter-assemblage variability is high in space and time, expressed in the quantitative relationship between elements of the production systems as well as in the specific technological procedures applied to core exploitation. This variability is not exclusively chronological or geographic.

At the same time, there are common features across east African assemblages. These include the use of local raw materials, typically from nearby channels, with selective criteria that emphasize quality for knapping/use. Another shared behavior is the use of flakes as LCT blanks and thinning of the butt and bulb of percussion. Large cores are either missing from the assemblages or, as is the case in MW, are uncommon ("scarce" in Peninj, de la Torre et al., 2008; 2.15% in Garba IVD, Gallotti, 2013). The technological procedures related to LCT production are spatially segmented (over typically short distances; e.g., de Heinzlein et al., 2000; de la Torre et al., 2008; Gallotti, 2013; Presnyakova et al., 2018). MW (and more so, Gadeb) may represent the longest procurement distances for the time ~1.5 to ~1.4 Ma. As a result, the raw materials are dichotomized (local and non-local) according to the two flaking systems. Another shared technological property of the early Acheulian assemblages is the paucity of retouched artifacts, except the occasional modification of large flakes into massive scrapers.

Temporal trends that are common to both the Rift and highland sites are related mostly to the production and use of LCTs. Where localities are well-contextualized stratigraphically, within-assemblage quantities of artifacts related to LCT maintenance and curation increase with time. Frequencies of handaxes, followed by cleavers, increase from ~1.4 Ma onward. The same is true of items associated with the Kombewa flaking method for large flake blanks (documented at localities KGA7-A2/A3 and KGA8-A1 (1.4−1.3 Ma) in Konso and in MW2-L1&L2 (at ~1.4 Ma) and MW5-L2 (at ~1.4−1.3 Ma) (Gossa, 2020; Sano et al., 2020). Finally, the LCT component takes on a more refined aspect due to higher investment in thinning and finishing stages. In stratified assemblages, this trend is linked to maintaining fairly standardized aspects of elongation and relative thickness (Gossa, 2020; Gowlett, 2013; Wynn and Gowlett, 2018). On the highlands, some techno-economic innovations appear earlier in MW than in other sites. Large-scale, systematic LCT production from boulders at the primary source emerged ~1.4 Ma ago in MW2-L1&L2 and in MW5-L2, while its first appearance in MK is in locality Garba XIII (1.0−0.87 Ma; Gallotti et al., 2014). The spatial segmentation of the lithic reduction sequences for LCTs is also encountered in MW at ~1.5−1.4 Ma, becoming more prevalent with time. The early occurrence of these novel behaviors in MW is contemporaneous with their appearance in the Rift (de la Torre and Mora, 2018; de la Torre et al., 2008; Presnyakova et al., 2018).

The precociousness of the MW technological trends is inconsistent with the association suggested by Gallotti and Mussi (2017) of the "early Pleistocene Acheulian" dated to more than 1.0 Ma in MK with *Homo erectus/ergaster* (Condemi, 2004; Di Vincenzo et al., 2015) and of the Acheulian < 1.0 Ma with *Homo heidelbergensis* (Profico et al., 2016). We note that while the time of emergence of *Homo heidelbergensis* remains unclear, fossils of the genus *Homo* known from the time span of the MW site-complex, less or more closely associated with Acheulian assemblages, are those of *Homo erectus/ergaster* (Abbate et al., 1998; Antón 2012; Asfaw et al., 1992; Grün et al., 2020; Potts et al., 2004; Rightmire, 2017; Semaw, 2020; Simpson et al., 2008). While no hominin fossils are currently known from MW, parsimony favors a working hypothesis that *Homo erectus* were the authors of the MW assemblages, pending new evidence. In this perspective, the technological changes observed within MW and across eastern Africa in the second half of the early Pleistocene are suggestive of behavioral adaptations/innovations within a single hominin taxon, rather than representation of taxon-related different cognitive abilities/adaptive requirements.

Taken together, the spatio-temporal distribution of technological aspects in sites later than 1.7 Ma suggests that once Acheulian-making hominins reached the highlands, the behavioral changes occurred more or less synchronously in the highlands and the Rift, without discernible behaviors that could testify to innovations in adaptive strategies. Combined with the argued authorship of *Homo erectus*, this would favor a mechanism of expansion during a time of low climate variability rather than dispersal and broadening of ecological niches, for the occupation of the highlands by Acheulian-making groups.

Clark's (1987) model of Rift-highlands connections presciently evoked a similar scenario. Based on the presence in Gadeb 8E of few handaxe made on obsidian, presumed to have originated from the Lake Ziway area, some 100 km to the west in the MER (Clark and Kurashina 1979b), Clark (1987) hypothesized that Acheulian-making *Homo erectus* expanded their home ranges compared to earlier hominins. He suggested a model in which their territorial ranges consisted of relatively small core areas in riparian forests adjacent to large permanent water bodies and expansive drier savanna areas. Clark envisioned a pattern of radiating mobility from multi-purpose persistent places (reminiscent of Isaac's [1971, 1978] 'home base' model), from which groups split into small foraging task-units for specific activities in the core and savanna areas. In this model, persistent places formed when discarded artifacts from previous visits attracted hominins repeatedly to the very same spot on the landscape, leading to the formation of high-density artifact clusters. A geomorphic prerequisite for such accumulations would be a stable landscape associated with low erosion rates (i.e., low energy fluvial systems; e.g., Altamura et al., 2020), whereas quick removal or burial (or a combination) of sediments (e.g., in deltaic or braided stream landscapes) would have obliterated visible cues of previous activities at a given location, reducing the chances of revisits, thus resulting in today's low-density archaeological localities. Clark (1987) suggested that high density sites were more likely to occur on the highlands, whereas more ephemeral and low-density occupations occurred more often in the Rift. Recent evidence from Melka Wakena and MK corroborates that highland archaeological horizons are associated with water bodies, but those are not always conducive to low erosion (e.g., MW1; Mendez-Quintara et al., 2019).

Mussi et al.'s (2016) model focuses on a larger temporal scale, suggesting cyclical, climate-driven movements of Acheulian-making groups away from the highlands (>2000 m amsl) during periods of colder climate, and their expansion back to the highlands during warmer periods. This is based on the record at the Gombore II sequence of MK, dated ~805–700 ka (MIS20-MIS19), during the middle Pleistocene transition. This model does not make specific predictions about the nature of the sites in each area.

While the two models address hominin movements at different temporal scales, both perceive of the highlands and Rift as complementary components of a novel adaptive system of *Homo erectus*. The lateral expansion onto the highlands may have been facilitated by the spatio-temporal availability of water in the Rift and escarpment during periods of water abundance, which may have created a network of affordances across rather than along the Rift axis (Cuthbert et al., 2017). High water levels in the Rift's "amplifier" lakes could also create barriers to movement within the Rift (Trauth et al., 2010) and trigger lateral expansion to the escarpment and highlands (and see Kübler et al., 2020 for a general discussion).

Testing of both models with the data at hand is not straightforward. While there are relatively many dated tephra in both MK and MW, the overall chronological resolution is insufficient to link periods of highlands occupation with either cold or warm MIS to successfully test the model of Mussi et al. (2016). This is because the deposits predating the middle Pleistocene transition fall within a time of multiple shifts between colder and warmer periods (MIS 56-MIS 20 [Lisiecki and Raymo, 2005]; (Fig. 3b; Supplementary table 2.2). To validly test the model, additional dates are required in tandem with analyses of site-specific paleo-ecology and of depositional context. Similarly, although the geomorphic contexts of localities from the MW and MK sites are broadly in agreement with Clark's model, a rigorous test of this model requires unpacking into its specific components and their independent assessments. Such analyses should focus on site-centered reconstruction of depositional contexts (using geomorphological and micromorphological methods), site-specific paleoecology (phytolith, stable isotope and plant wax analyses), and in-depth archaeological studies of site structure and function (relying on analyses of lithic raw material economy and production, lithic use-wear studies and archeozoological studies), to distinguish between diverse-function sites and locations of focused activities such as workshops and butchery sites.

The two models of hominin behavior at the Rift-highlands interface invoke high behavioral variability during a time characterized by low variability of orbitally-driven climate trends. Indeed, a growing number of researchers have noted that climate and ecological trends respond to different thresholds (see, e.g., Maslin, 2004 and references therein) and are not necessarily synchronous. Climate changes are variably regionalized through topography, continental or regional climate systems and geographic location. The coping mechanisms of hominins can be more effectively contextualized by using a bottom-up approach rather than a conceptual umbrella of inclusive models (see for example Behrensmeyer, 2006; Cuthbert et al., 2017; Maslin et al., 2014; Patterson et al., 2017; Rohling et al., 2013; Trauth et al., 2010). This appears to also be the case for the early Acheulian on the Ethiopian highlands.

8. Conclusions

Recent work at the newly discovered site of MW revealed a sequence of archaeological localities dated to the second half of the early Pleistocene, dated by $^{40}Ar/^{39}Ar$ to between 1.6 Ma and >0.7 Ma, significantly enlarging the number of sites from this period known from the highlands of eastern Africa. A paleogeographic reconstruction based on detailed stratigraphic logging suggests the localities are found in an area where sediments, transported by channels flowing off the high Bale mountain range and from the gentle slopes occupied by the Nazareth Series, were deposited on a low-relief plain. This led to the formation of a network of channels, ponds and ox-bow lakes that were the backdrop for hominin occupations. The small faunal assemblages indicate a mixed community of aquatic, water-dependent and open-landscape species, but sample size is not sufficient to determine if species composition is due to environmental change or to changes in hominin locational preference in relation to water courses.

The nine archaeological horizons tested to date are associated with the Acheulian technocomplex. The MW Acheulian is similar in age to other highlands sites, all suggesting that this technocomplex first occurred on the plateau slightly later than in the Rift. The assemblages show reduction systems for both small debitage and LCTs made on large flakes, each associated with a different raw material procurement strategy. The use of glassy ignimbrite from off-site sources located 4–5 km away from the site suggests a spatial segmentation of the technological process beginning at least at ~1.4 Ma. The frequencies of LCTs in the assemblages increased with time, concurrent with their refinement through higher investment in late-phase shaping procedures, whereas core reduction for small flakes indicate attempts to increase core use lives. Analysis of the lithic assemblages indicates some components of the technological system seem to emerge at MW slightly earlier than in the site of MK, from which data are available for such comparisons. Technological novelties and temporal trajectories in LCT production are broadly coeval with those observed in the Rift assemblages. This supports an understanding of the highlands occupation as a process of geographic expansion, suggesting that the early sites on the highlands should not be separated from the cultural and biological developments in the Rift, even if environmental differences were on the scale that is observed between the two regions today (Section 1.2).

The discovery of MW enlarges the modest database of highlands Acheulian occupations. When considered in the context of the Rift-highlands interface, the results reported here from the first-phase research at the site underscore the possibility of unpacking general models into archaeologically testable hypotheses. The results demonstrate the site's potential to contribute to research of early prehistory and to understanding the dynamics of hominin cultural evolution, mobility and range expansion in the early Pleistocene of eastern Africa.

Author statement

Hovers and Gossa co-directed the project, raised the funding and organized all aspects of the work. All the authors but Niepsolo and Renne participated in fieldwork and all the authors contributed to the post-excavation analyses and to the preparation of the manuscript. EH conceived the framework of the paper, synthesized the input from authors and wrote the introduction, discussion and conclusions sections. TG provided data and text on the lithic assemblages. Asrat and Resom conducted the geological fieldwork and provided text related to stratigraphy and sedimentology. Niespolo and Renne conducted the dating analyses and provided the text related to it. MBN excavated, studied and described the faunal material. RE and GH conducted the surveying and measuring part of all excavations, organized the spatial data, and worked with

TG to digitize and prepare graphics. NK acted as field surpervisor and provided important insights. All authors participated actively in the editing of the paper, commented on several drafts and approved the one submitted.

Declaration of competing interest

All authors declare no conflict of interests.

Acknowledgments

We thank the Authority for Research and Conservation of Cultural Heritage (ARCCH) of Ethiopia for its encouragement and help during the field and post-excavation phases of the study. We are grateful to the people of Aluba village for their hospitality and help in the field and beyond. Work at Melka Wakena was supported by grants from the Palaeontological Scientific Trust (PAST), National Geographic Society (Grant #9801–15), Gerda Henkel Foundation, and the Ruth Amiran Fund for Archaeological Research at the Institute of Archaeology, The Hebrew University of Jerusalem. TG's doctoral studies were supported by a Wadsworth Fellowship from the Wenner-Gren Foundation and a Baldwin Fellowship from the Leakey Foundation. The field geological and stratigraphic work was supported by the School of Earth Sciences, Addis Ababa University as part of AR's Masters studies under the supervision of AA. EMN was supported by a U.C. Berkeley Fellowship. The geochronology work was supported by the Ann and Gordon Getty Foundation and by a grant from the John Templeton Foundation. BMN thanks the Spanish Ministry of Science (grant CGL-2016-80975-P), Generalitat de Catalunya (grant GENCAT 2017SGR 859) and Palarq Foundation. Photographs of the fauna were prepared by Sergio Ros-Montoya. This paper was written when EH was a visiting researcher at the Dept. of Anthropology, NYU, in the academic year 2019/2020.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2020.106763.

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