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Geology and chronology of the Ndutu and Naisiusiu type sites: implications for Middle and Later Stone Age occupations at Olduvai Gorge (Tanzania)

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A R T I C L E I N F O

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A B S T R A C T

Olduvai Gorge (northern Tanzania) preserves a rich and continuous paleoanthropological record spanning the past two million years. While its Early Stone Age occupations have been intensively studied, the Middle and Later Stone Age sequences, represented by the Ndutu and Naisiusiu Beds, remain less understood. This study presents new geological and geochronological data from the type localities of the Ndutu and Naisiusiu Beds. Using optically stimulated luminescence (OSL), we establish a revised chronological framework for these sedimentary units. The Lower Ndutu Beds, composed of fluvially reworked conglomerates and sands capped by a trachytic tuff and silts, are now dated between 152.9 ± 11.6 ka and 122.9 ± 8.3 ka. The Upper Ndutu Beds include archaeologically rich sandy and silty facies and are dated between 86.9 ± 4.5 ka and 70.8 ± 10.4 ka. At the Naisiusiu type site, a sequence of fluvial, sheetwash, and aeolian deposits yielded OSL dates ranging from 65.3 ± 4.4 ka to 32.8 ± 2.2 ka, suggesting that the LSA occupation at Olduvai began significantly earlier than previously assumed. These results provide refined age estimates for the Middle and Later Stone Age deposits at Olduvai Gorge and confirm a relatively rapid transition between these two technocomplexes during the Late Pleistocene. The data strengthen regional correlations with sites like Nasera and Mumba, providing critical chronological resolution to ongoing debates about the tempo and mode of behavioural evolution in eastern Africa.

1. Introduction

Olduvai Gorge, in northern Tanzania, is considered a significant paleoanthropological site for studying human evolution and behaviour during the Pleistocene. The gorge preserves an exceptional sedimentary sequence approximately 100 m thick spanning the last 2.1 million years (Hay, 1976). This makes Olduvai a natural archive of tectonic, climatic, and paleoenvironmental changes that have shaped hominin evolution.

The geology of Olduvai Gorge was initially outlined by Hans Reck in the early 20th century (Reck, 1914), but it was Richard Hay who formalised the sequence still in use today. Hay (1976) divided the stratigraphy into several major units: Beds I through IV (Early to Middle Pleistocene), followed by younger units known as the Masek, Ndutu, and Naisiusiu Beds (Middle to Late Pleistocene). These formations record a

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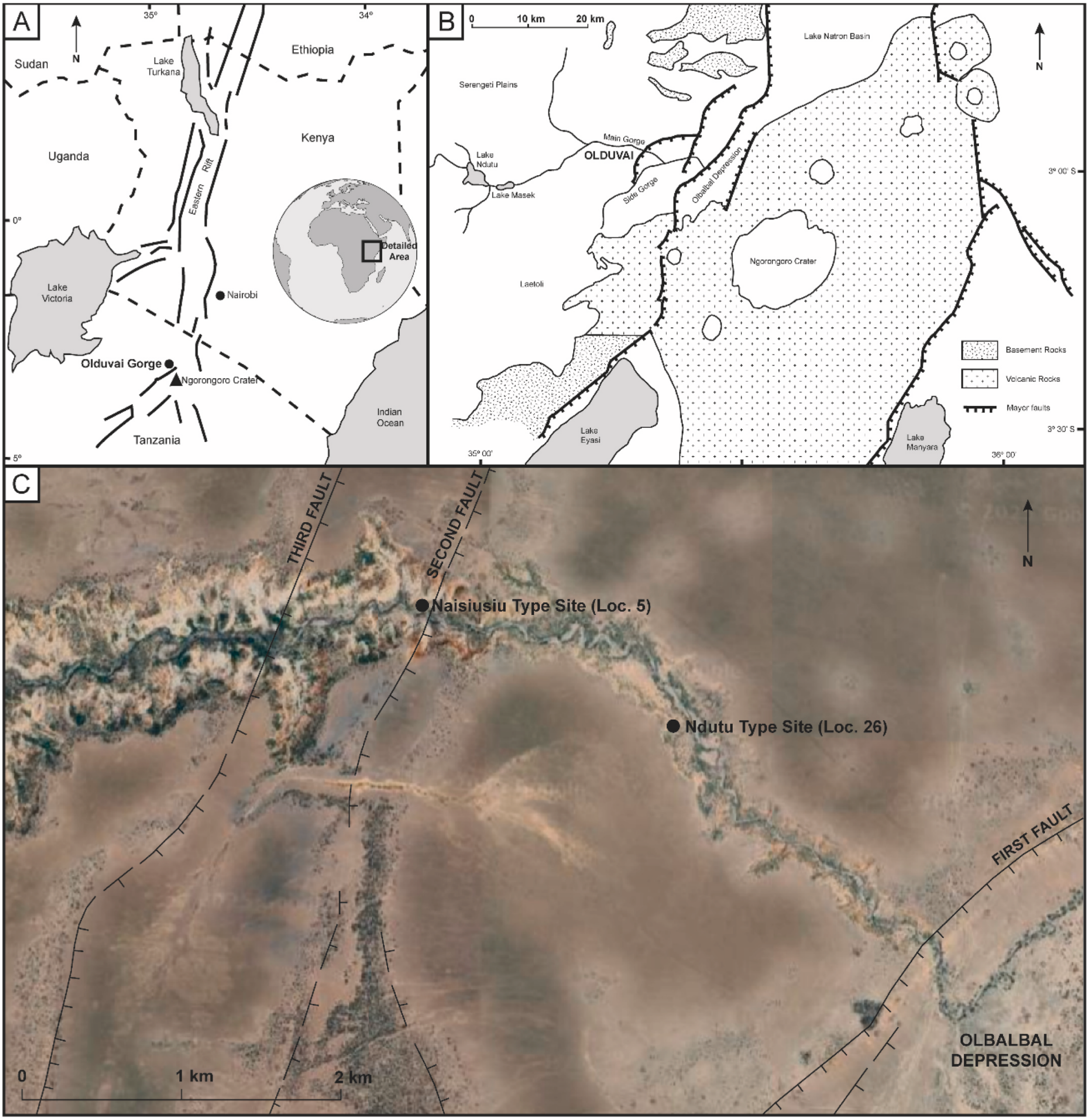

Fig. 1. **A.** Map of eastern Africa indicating the position of Tanzania and Olduvai Gorge. Modified from Ashley and Hay (2002). **B.** Map of the Ngorongoro Volcanic Highlands and surrounding Olduvai Gorge region, highlighting major fault systems. Modified from Hay (1976) and McHenry (2012). **C.** Location of the First, Second and Third Faults along the Main Gorge and the Ndutu and Naisiusiu type sites. Orthoimage taken from Google Earth (2023).

complex interplay of fluvial, lacustrine, and aeolian processes influenced by tectonic activity and volcanism from nearby systems in the Ngorongoro Volcanic Highlands.

From the 1930s onward, pioneering excavations by the Leakey family and subsequent research teams uncovered abundant archaeological and hominin material, focusing on the older units (Beds I–IV) in Early Stone Age (ESA) contexts. These units have yielded Oldowan and Acheulean stone tool industries alongside fossil remains of *Homo habilis*, *Paranthropus boisei*, and *Homo erectus* (Leakey, 1959, 1961; Leakey, 1971; Blumenschine et al., 2003; Domínguez-Rodrigo et al., 2015, 2018). Sites such as FLK-Zinj, DS, FLK-West and TK have been pivotal and transformed interpretations of early technological and adaptive behaviours in Pleistocene hominins (Leakey, 1959, 1961, 1971; Domínguez-Rodrigo et al., 2010, 2013; Blumenschine et al., 2012; Díez-Martín et al., 2015, 2019; Mercader et al., 2020; Bello-Alonso et al., 2021; de la Torre et al., 2021, 2025).

While these older units (Beds I–IV) have received the bulk of scholarly attention, the younger Ndutu and Naisiusiu Beds have historically received limited attention (Leakey et al., 1972; Mabulla, 1990; Skinner et al., 2003; Eren et al., 2014; Maíllo-Fernández et al., 2019a, 2022;

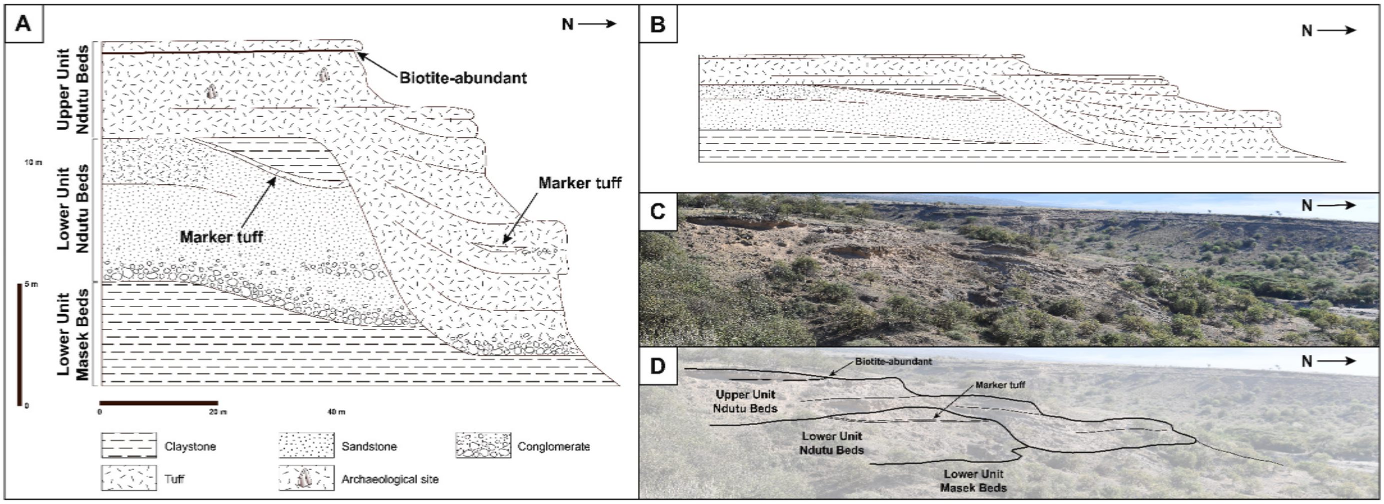

Fig. 2. The Ndutu type site. **A.** Cross-section of the Lower and Upper Ndutu Beds at locality 26, the type site. Modified from Hay (1976). **B.** The same cross-section, without any vertical exaggeration. Modified from Hay (1976). **C.** Photograph of the Ndutu type site. **D.** Interpreted photograph of the Ndutu type site.

Solano-Megías et al., 2025). Although early references to MSA artefacts at Olduvai date back to Leakey et al. (1972), systematic excavations have been limited until recent years. Renewed research at sites such as the Victoria Cabrera Site (VCS, near Locality 42; Maíllo-Fernández et al., 2019a) and the Dorothy Garrod Site (DGS, near Locality 20; Maíllo-Fernández et al., 2022; Solano-Megías et al., 2025) has begun to change this field of study. MSA assemblages characterised by Discoidal and Levallois methods have been recovered and securely dated, extending the occupational sequence of Olduvai into the Late Pleistocene and enhancing our understanding of the MSA–LSA transition (Maíllo-Fernández et al., 2019a, 2022; Solano-Megías et al., 2025).

The interpretation of the Ndutu and Naisiusiu Beds faces significant challenges stemming from the lack of reliable chronostratigraphic control, primarily due to the scarcity of dateable volcanic tuffs. Initial age estimates were derived from radiocarbon dating and amino acid racemisation (Hay, 1976; Leakey et al., 1972), often with significant uncertainties. Recent decades have seen significant improvements in chronological resolution due to the application of advanced techniques such as $^{40}Ar/^{39}Ar$ dating, electron spin resonance (ESR), and optically stimulated luminescence (OSL; Deino et al., 2021; Smedley et al., 2024).

Given the growing number of archaeological discoveries within the Ndutu and Naisiusiu Beds and the persistent chronological uncertainties, this study integrates new and existing geological, geochronological, and archaeological datasets to refine the depositional history of these units. This study focuses on the type sites where these key stratigraphic units were initially described. The objective is to contextualise the MSA and LSA assemblages within a well-constrained temporal and geological framework, thereby contributing to the broader discourse on human behavioural evolution during the Late Pleistocene in eastern Africa.

2. Geological and geographical context

Olduvai Gorge is situated within the eastern African Rift System, west of the Ngorongoro Volcanic Highlands (Fig. 1), and has served as a depocenter for Paleolake Olduvai since approximately 2.25 Ma (Hay, 1976; Deino et al., 2021). The basin's stratigraphy was initially described through outcrop studies (Reck, 1914; Hay, 1976) and later refined through the Olduvai Gorge Coring Project (OGCP), which provided a detailed chronostratigraphic framework based on borehole data (Stanistreet et al., 2020). The gorge reveals a well-preserved 100-m-thick sequence of lacustrine, fluvial, alluvial fan, and aeolian deposits. These deposits record major environmental and climatic fluctuations that influenced hominin evolution (Cerling and Hay, 1986; Ashley, 2007). The Ndutu and Naisiusiu Beds were first described at their respective type localities: the Ndutu type site is situated at Locality 26, while the Naisiusiu type site lies approximately 110 m west of the Second Fault (Fig. 1C).

2.1. Ndutu Beds

The Ndutu Beds, predominantly fluvio-aeolian in origin, rest disconformably on the older, underlying Beds, with their basal contact marked by an erosional unconformity coated with laminated calcretes (Hay and Reeder, 1978). These deposits have been recorded as being up to 24 m thick in the Main Gorge and approximately 10 m at the type section (Locality 26; Fig. 2), and are intensely controlled by synsedimentary faulting (Hay, 1976). The Ndutu Beds are divided into two units: (1) the Lower Ndutu Unit, comprising fluvially dominated conglomerates, sandstones, and volcaniclastics, including a trachytic marker tuff approximately 22 m above the riverbed; and (2) the Upper Ndutu Unit, dominated by conglomerates and aeolian tuffs (Hay, 1976).

Early constraints on the maximum age of the Ndutu Beds were derived from the Norkilili Tuff, found at the top of the Masek Beds. The predominantly aeolian and fluvial deposits of the Masek Beds represent the final phase of sedimentation prior to a major erosional event that not only started shaping the gorge but also created the accommodation space in which the Ndutu Beds were subsequently deposited. Potassium-argon (K/Ar) dating of the Norkilili Tuff placed the formation of the Masek Beds between 1.1 and 0.4 million years ago (MacIntyre et al., 1974).

Initial age estimates for the Lower Ndutu Beds were based on a combination of methods, including amino acid racemisation (AAR) of fossil bone, uncalibrated radiocarbon dates, and inferred correlations with volcanic activity from Kerimasi and Oldoinyo Lengai. These approaches suggested that the Lower Ndutu Unit was deposited between approximately 400 and 60 ka (Hay, 1976).

More recent advances have significantly refined this chronological framework. Integration of high-resolution $^{40}Ar/^{39}Ar$ dating of tuffs and reworked pyroclastic deposits with magnetostratigraphic data enabled the development of a Bayesian age-depth model by Deino et al. (2021). This model places the basal contact between the Ndutu and Masek Beds sometime between 0.33 and 0.50 Ma. In the same model, the base of the Masek Beds was dated to 0.82 ± 0.06 Ma and 0.64 ± 0.09 Ma.

Chronological interpretations of the Upper Ndutu Beds have evolved significantly. Originally estimated by Hay (1976) to range between 60 and 32 ka, these estimates were later challenged by Manega (1993), who proposed a broader range of 549–210 ka using single-crystal laser fusion techniques and AAR.

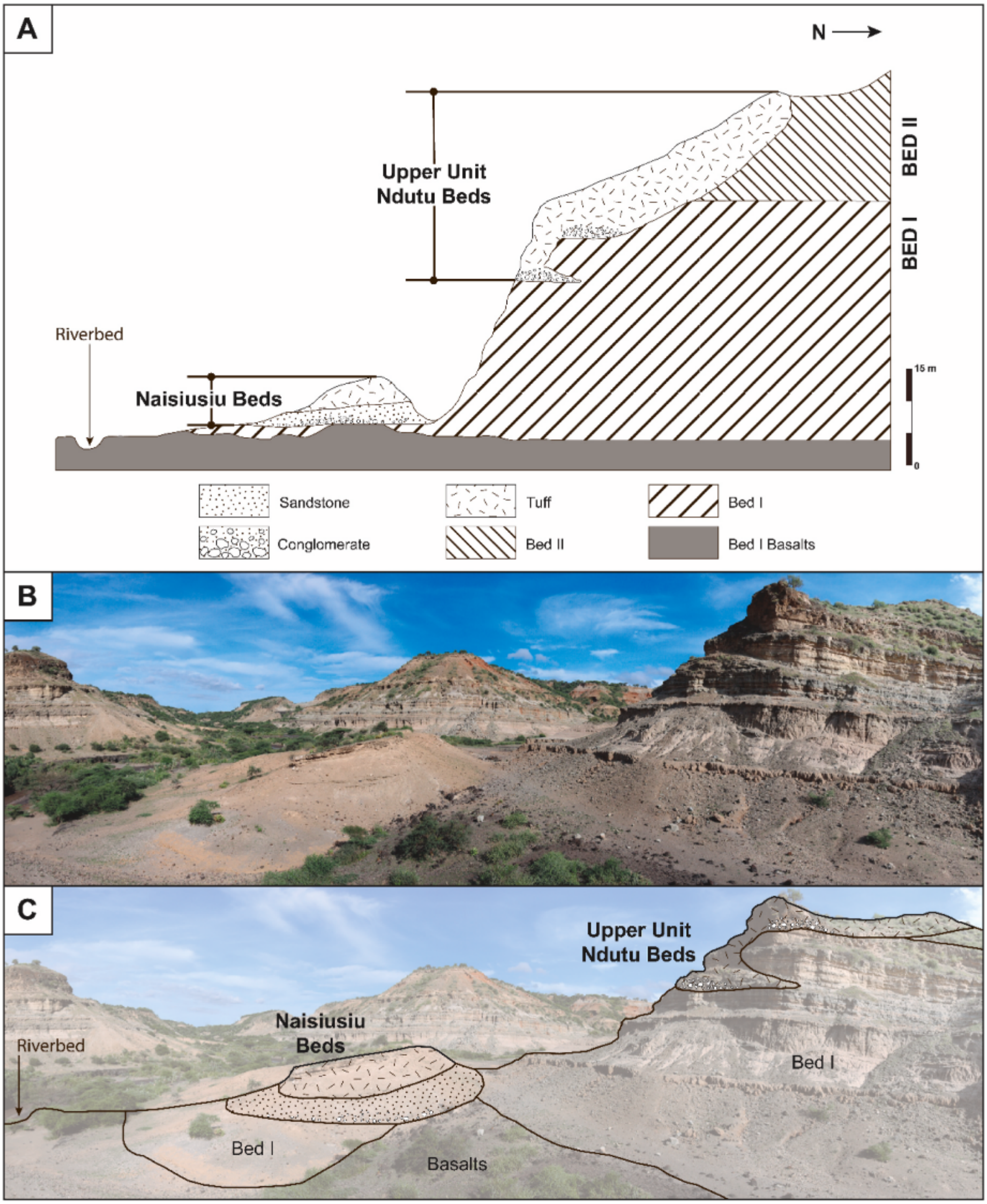

Fig. 3. The Naisiusiu type site. **A.** Cross-section illustrating the Naisiusiu Beds and the upper Ndutu Unit at their type section, located 110 m west of the Second Fault. Modified from Hay (1976). **B.** Photograph of the Naisiusiu type site. **C.** Interpreted photograph of the Naisiusiu type site.

More recently, Maíllo-Fernández et al. (2019a) reported three optically stimulated luminescence (OSL) ages from a trench excavated at VCS. These luminescence dates bracketed this MSA lithic assemblage between 86.2 ± 5.5 ka and 76.3 ± 5.2 ka, suggesting that cultural activity within the Upper Ndutu Beds extended further back than previously assumed, but not as much as proposed by Manega (1993). Shortly after, Smedley et al. (2024) developed a high-resolution luminescence-based age-depth model using fifteen samples from OGCP boreholes. Their results date the Upper Ndutu Beds between 117.1 ± 17.9 ka and 45.3 ± 4.2 ka (with modelled ranges of 125.9 ± 26.5 ka to 45.8 ± 8.2 ka).

While the work by Smedley et al. (2024) provides a robust and high-resolution chronology for the uppermost section of the Upper Ndutu Unit, their sampling was limited to the terminal part of the sequence intersected in the OGCP boreholes. In contrast, this study examines the complete sedimentary successions exposed at the Ndutu type locality, encompassing both the Upper and Lower Ndutu Units. By targeting chronometric sampling throughout the complete stratigraphic sequences, we aim to establish a broader framework for the depositional history of the Ndutu Beds and their associated archaeological horizons.

Table 1
Post-Infrared-Infrared at 225 °C protocol (Buylaert et al., 2009) was used to measure the individual natural doses.

pIR-IRSL225
Natural or given dose
PH (250 °C, 60 s)
IRSL (50 °C, 200 s)
IRSL (225 °C, 200 s)
Test Dose 10 Gy
PH (250 °C, 60 s)
IRSL (50 °C, 200 s)
IRSL (225 °C, 200 s)
IR Cleanout (290 °C, 200 s)

Table 2
Data related to luminescence dating. It includes the radionuclide concentration, sample depth used for calculating the cosmic contribution, total dose rates, estimated burial doses and derived ages; the former expressed in ka and reported at 1-sigma associated uncertainty.

Sample	Lab code CENIEH	Depth (m)	U (ppm)	Th (ppm)	K (%)	Rb (ppm)	Dose rate (Gy/ka)	Burial dose (Gy)	Age (ka)
NS-03	LM22184-09	0.5	1.20 ± 0.04	17.7 ± 0.6	2.49 ± 0.05	67.6 ± 2.1	4.67 ± 0.22	153.2 ± 7.4	32.8 ± 2.2
NS-02	LM22184-08	4.0	1.64 ± 0.05	19.0 ± 0.7	2.89 ± 0.06	80.2 ± 2.5	5.11 ± 0.23	231.4 ± 21.0	45.3 ± 4.6
NS-01	LM22184-07	6.0	4.08 ± 0.11	17.2 ± 0.6	2.70 ± 0.05	80.3 ± 2.5	5.31 ± 0.24	346.6 ± 17.3	65.3 ± 4.4
NDU-04	LM22184-05	0.8	1.25 ± 0.04	10.3 ± 0.4	3.25 ± 0.06	74.3 ± 2.3	4.86 ± 0.23	344.3 ± 47.8	70.8 ± 10.4
NDU-03	LM22184-04	1.0	1.16 ± 0.03	9.9 ± 0.3	1.91 ± 0.04	44.5 ± 1.4	3.64 ± 0.19	316.3 ± 23.8	86.9 ± 8.0
NDU-01	LM22184-02	1.0	1.96 ± 0.05	16.9 ± 0.6	3.14 ± 0.06	93.8 ± 2.9	5.33 ± 0.24	462.2 ± 11.9	86.8 ± 4.5
NDL-03	LM22184-06	2.0	1.59 ± 0.04	16.7 ± 0.6	2.95 ± 0.06	91.3 ± 2.8	5.04 ± 0.23	619.7 ± 31.1	122.9 ± 8.3
NDL-02	LM22184-11	1.0	2.08 ± 0.06	13.6 ± 0.5	2.73 ± 0.05	78.2 ± 2.4	4.78 ± 0.22	629.1 ± 39.8	131.6 ± 10.3
NDL-01	LM22184-10	1.0	3.56 ± 0.09	17.3 ± 0.6	1.61 ± 0.03	49.6 ± 1.5	4.34 ± 0.21	663.8 ± 39.4	152.9 ± 11.6

2.2. Naisiusiu Beds

The Naisiusiu Beds are preserved as erosional remnants inside the Main Gorge (Fig. 3) and extend as a discontinuous sheet over the Serengeti Plain, unconformably overlying older Beds. These deposits, ranging from 0.3 to 10 m in thickness, accumulated after the major phases of tectonic activity that shaped the Olduvai Basin (Hay, 1976). The Naisiusiu Beds consist of three subunits: (1) basal fluvial sediments, (2) middle sheetwash deposits, and (3) upper aeolian tuffs (Leakey et al., 1972; Hay, 1976). An undated yellow marker tuff is found in the uppermost section of the sheetwash deposits (Hay, 1976).

The age of the Naisiusiu Beds has long been debated due to conflicting chronometric evidence and methodological limitations. Mehlman (1987, 1989) initially proposed that these deposits corresponded with the Last Glacial Maximum (LGM), around 20–19 ka, based on technological parallels between the lithic assemblages at Naisiusiu and those of the Lemuta industry at Nasera rockshelter, located to the north of Olduvai Gorge.

Supporting this general timeframe, Manega (1993) applied single-crystal laser fusion (SCLF) $^{40}Ar/^{39}Ar$ dating to biotite crystals in phonolithic tuffs from the lower part of the Naisiusiu Beds, yielding an age of 42 ± 10 ka. However, this interpretation has been contested by electron spin resonance (ESR) dating of equid teeth from the same unit, which produced ages of 62 ± 5 ka and 39 ± 5 ka (Skinner et al., 2003; Millard, 2008). These ESR dates imply that LSA occupations preserved in the Naisiusiu Beds could extend from approximately 67 to 34 ka, thus predating the LGM.

Adding to this complexity, Smedley et al. (2024) proposed that two of their luminescence-dated samples, obtained from OGCP Core 3B, likely correspond to the Naisiusiu Beds. These yielded ages of 23.7 ± 10.9 ka and 12.1 ± 1.7 ka, with modelled ranges of 25.7 ± 18.9 ka and 12.0 ± 3.4 ka, respectively. If correct, these results would support a more recent age range for at least part of the Naisiusiu sequence, aligning it more closely with previous hypotheses linking it to the LGM or the Holocene onset.

Given these inconsistencies and uncertainties, one of the key objectives of this study is to produce new chronological data for the Naisiusiu Beds, based on samples collected directly from the type locality. We aim to refine the temporal framework of this poorly constrained unit and clarify its role within the broader context of LSA occupations at Olduvai Gorge.

3. Materials and methods

3.1. Luminescence dating

Samples for luminescence measurements were collected by hammering opaque tubes horizontally into the target levels. From each sample, feldspar grains of sizes 180–250 μm were extracted using standard procedures which included hydrochloric acid and peroxide treatments to remove carbonates and organic matter, respectively, followed by density separation to extract the potassium feldspar (<2.58 g/cm^3) fraction.

K-feldspar 2 mm multi-grain aliquots (containing approximately 20 grains each) were measured to obtain representative dose distributions as this aliquot size has shown to provide enough resolution on doses to identify partial bleaching (Gaar et al., 2014), following the post Infrared-Infrared Stimulated Luminescence at 225 °C protocol (postIR-IRSL225; Buylaert et al., 2009, Table 1). This protocol was chosen as it has been shown to minimise the effect of anomalous fading (Thomsen et al., 2008). Nevertheless, the fading rates were tested by calculating the g-value, which quantifies the rate at which the luminescence signal decays over time. The g-value is expressed as a percentage of the signal loss per decade. Dose recovery tests were carried out to confirm the suitability of the measurement protocol and select the most appropriate measurement conditions. These were measured on aliquots bleached in a solar simulator for 24h and artificially irradiated using the built-in ^{90}Sr source in a Risø luminescence reader. Given and measured doses, both natural and artificial, are expressed in grey (Gy), the SI unit for ionizing radiation absorbed dose.

The equivalent doses were estimated by applying the Central Age Model (CAM; Galbraith et al., 1999) to the population derived from the measurement of the pIR-IRSL signal at 225 °C of 14–24 aliquots of each sample. It was not possible to measure a larger number of aliquots for samples LM22184-04 and −05 (NDU-03 and 04) due to the scarcity of material available.

In addition to that in the opaque tubes, extra material was collected to measure the radionuclide concentration, needed for the external dose

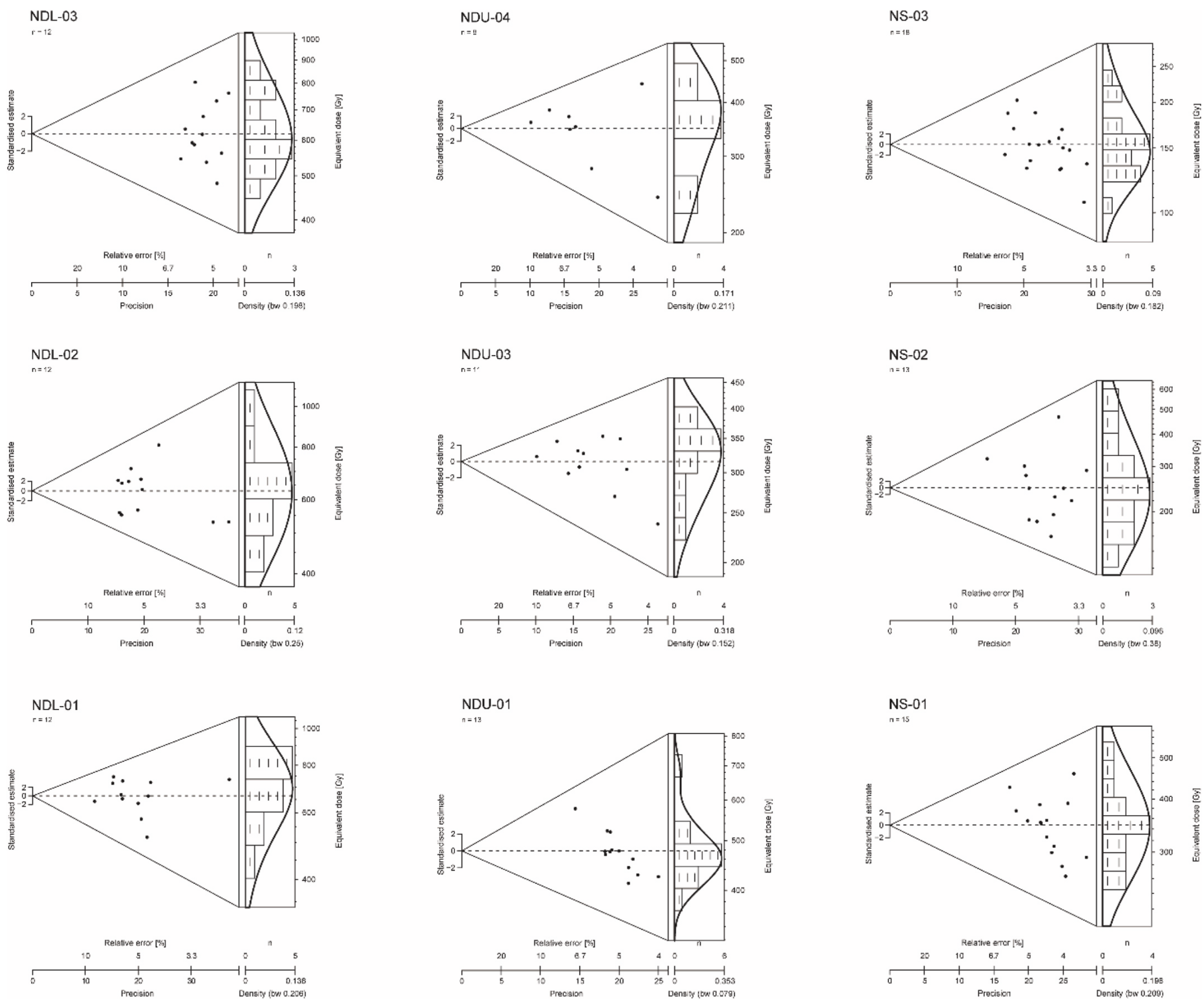

Fig. 4. Dose distributions derived from the pIR-IRSL225 signal of K-feldspar 2-mm multigrain aliquots. The plots show the radial plots, indicating the dose values against their precision and the corresponding kernel density estimates.

rate calculation. The concentration of U, Th, K and Rb from each matrix, obtained from ICP-MS (Table 2), was converted into external beta and gamma dose rates (Liritzis et al., 2013) and an external alpha contribution was calculated according to an a-value of 0.10 ± 0.02 (Rees-Jones, 1995). An internal K concentration of 10 ± 2 % (Smedley et al., 2012) was assumed and the contribution of the cosmic radiation was calculated according to Prescott and Hutton (1994). In situ water contents vary between 6 and 12 %; an average value of 10 % with an added uncertainty of ±5 % to account for variations in the water content during the burial period was used to calculated attenuation of the dose by moisture. Total dose rates (Table 2) were calculated using the Dose Rate and Age Calculator (DRAC, Durcan et al., 2015).

3.2. Stratigraphy and sedimentology

Lithostratigraphic units were systematically documented through direct observation, scaled photography, measured sections, and detailed hand-drawn logs. Descriptions were based on key sedimentological attributes, including grain size, sedimentary structures, mineral composition, colour, and stratigraphic boundaries. Grain size was classified following Blott and Pye (2012). Sediment colour was objectively recorded using the Munsell Soil Colour Charts (Munsell, 1981), with dry samples classified according to hue, value, and chroma. Stratigraphic sections were logged covering the whole sedimentary sequences of the Upper Ndutu, Lower Ndutu and Naisiusiu units at their respective type localities.

4. Results

4.1. Luminescence dating results

The dose recovery tests performed showed no difference in the response when using a test dose of ~200 Gy (approximately 50 % of the natural measured dose) or a test dose of 10 Gy (<15 % of the natural dose) in contrast to observations by Colarossi et al. (2018) but similar to the IRSL behaviour of K-feldspar from the Atacama Desert (Medialdea et al., 2022). The recovered dose was within 10 % of the given dose in all cases. Since no differences were observed, but the measurement time was significantly reduced using a low-test dose, 10 Gy was used to measure the natural doses.

Fading tests performed on 5 aliquots of samples NDU-03, NS-03, and NDL-01 led to g-values between 0.2 ± 0.9 and 0.7 ± 0.6 %/decade for

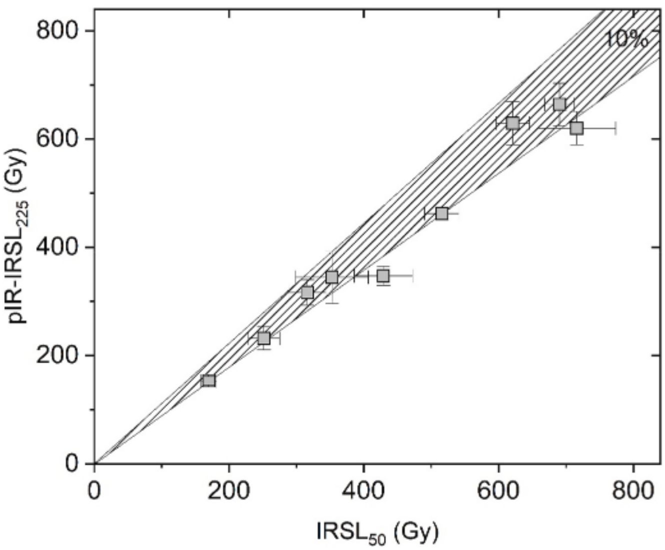

Fig. 5. Comparison between the estimated dose from the IRSL at 50 °C and the pIR-IRSL at 225 °C. As these two signals have different bleaching rates, the agreement between them indicates that the samples in this study are not affected by incomplete bleaching. The shaded area shows the 10 % region.

the pIR-IRSL225 signal, low values with large associated uncertainties similar to those previously measured on feldspar from this region (Smedley et al., 2024). The effect of anomalous fading is not significant for this signal, and a correction of the estimated doses and corresponding ages was not necessary.

The natural dose distributions (Fig. 4) show overdispersion values, OD, ranging between 20 and 30 %. The potential partial resetting of the grains during transport, which could lead to an overestimation of the burial dose, has been discarded by comparing the IRSL signal at different temperatures. It has been reported that IRSL at 50 °C and pIR-IRSL at 225 °C bleach at different rates (Murray et al., 2012). It is to be expected that the $IRSL_{50}$ would show larger doses than the corresponding pIR-$IRSL_{225}$ if these were affected by incomplete bleaching. Fig. 5 shows that estimated doses at the two different temperatures are in agreement within 10 % and it can then be concluded that these samples were well-bleached prior deposition. The CAM weighted mean (Galbraith et al., 1999) has therefore been considered appropriate to estimate the burial dose of each sample. The derived ages are summarised in Table 2.

4.2. Lower Ndutu stratigraphy

The Lower Ndutu sequence at the Ndutu type locality disconformably overlies the Masek Beds across an erosional contact (Figs. 2 and 6; Table 3). Overlying this erosive surface is a 40 cm-thick, greyish brown (10 YR 5/2) cross-stratified sandy layer (Unit NDL1). Above NDL1, the sequence is characterised by five stacked fining-upward sequences (NDL2 to NDL6), ranging in thickness from 8 to 70 cm and bound by erosive contacts. These sequences' colour varies from grey (10 YR 5/1) to greyish brown (10 YR 5/2). They transition from polymictic, clast-supported conglomerates to sands. The grain size grading within each sequence follows a consistent trend: from very small boulders, to medium-to-coarse gravel, to fine gravel and sand towards the top. The clasts are subrounded, exhibiting medium to high sphericity, and are composed of tuff, basalt and quartzite. Two dated units (Units NDL5 and NDL6) provide chronometric control within these sequences. Unit NDL5 yielded an OSL age of 152.9 ± 11.6 ka, while NDL6 returned a date of 131.6 ± 10.3 ka (Table 2).

Above NDL6, a 25 cm-thick, white (10 YR 8/2), fine to medium-grained trachytic vitric tuff (NDL7) is preserved. The Lower Ndutu sequence ends with a massive, very pale brown (10 YR 7/3), 1.8-m-thick tuffaceous silt to very fine sand (NDL8). NDL8 has been dated to 122.9 ± 8.3 ka (Table 2).

4.3. Upper Ndutu stratigraphy

At the Ndutu type locality, the Upper Ndutu sequence disconformably overlies both the Masek Beds and the Lower Ndutu sequence (Figs. 2 and 7; Table 4). The basal contact is marked by an erosional surface, above which a <10-cm-thick, polymictic clast-supported conglomerate (NDU1) is preserved. This unit is composed of fine to medium gravel, with rounded, spherical clasts of basalt and quartzite, set in a grey sandy matrix (10 YR 6/1).

Unit NDU1 is disconformably overlain by NDU2, a 90 to 100-cm-thick heterolithic and polymictic clast-supported conglomerate composed mainly of medium to coarse gravel, with abundant very coarse gravel and some small boulders. Clasts are predominantly basalt and quartzite, with minor components of tuff and phonolite. The matrix is a sparse grey sand (10 YR 6/1). Overlying this unit is NDU3, a 140 cm-thick unit of very pale brown (10 YR 7/3) silt to very fine sand. This unit, dated to 86.8 ± 4.5 ka (Table 2), contains archaeological material.

The upper part of the sequence comprises four discrete units—NDU4, NDU5, NDU6, and NDU8—ranging in thickness from 1 to 2.5 m. These units consist of medium to coarse sandstones, with localised laminae of finer, biotitic composition. Occasional coarser (fine to medium gravel) passings. These four units are heavily cemented with calcium carbonate (effervescing with hydrochloric acid) and display a light brownish grey colour (10 YR 6/2). Lithic remains can be found embedded in these units. Chronometric data include an OSL age of 86.9 ± 8.0 ka for NDU4 and 70.8 ± 10.4 ka for NDU8.

Between NDU6 and NDU8 lies a <10 cm-thick, biotite-enriched layer (NDU7), referred to by Hay (1976) as the "biotite-rich bed" (Figs. 2 and 7). This marker unit is traceable throughout the Upper Ndutu Beds exposures along the Main Gorge.

4.4. Naisiusiu stratigraphy

At the type site, the Naisiusiu Beds disconformably overlie tuffs, claystones, and basalts of Bed I (Fig. 3). The stratigraphic sequence (Fig. 8, Table 5) is subdivided into three units, following the framework described initially by Leakey et al. (1972) and Hay (1976): (1) basal fluvial sediments, (2) middle sheetwash deposits, and (3) upper aeolian tuffs. Only the uppermost 20 cm of the basal fluvial sediments were exposed in the excavated trench. This portion consists of a fining-upward sequence transitioning from a clast-supported conglomerate of fine to coarse gravel to a fine augitic sand. Clasts are well rounded, spherical, and primarily composed of basalt and quartzite.

The overlying sheetwash deposits (Units NAI2–NAI10) are composed of poorly sorted, fine to medium tuffaceous sands, varying from laminated to massive. These beds may contain lapilli and coarser passings. Two matrix-supported conglomerate units are interbedded within this sequence (Units NAI5 and NAI9), containing clasts of basalt and tuff. Units NAI4 and NAI6 include abundant faunal and lithic material. Embedded within this middle section is Unit NAI8, a <10 cm-thick, pale yellow (2.5 YR 8/4) to very pale brown (10 YR 8/3), fine to medium-grained phonolitic tuff. This bed was previously identified by Hay (1976) as a marker tuff. The archaeological assemblage described in Leakey et al. (1972), located 1 m below the marker tuff, is embedded in the upper section of Unit NAI4 (Fig. 8). Chronometric data from the sequence include an OSL age of 65.3 ± 4.4 ka from the base of the sequence (Unit NAI2) and 45.3 ± 4.6 ka from Unit NAI7, located immediately beneath the marker tuff (Table 2).

The upper part of the sequence (Units NAI11–NAI12) consists of very pale brown (10 YR 7/3) to light brownish grey (10 YR 6/2) massive silts to very fine tuffaceous sands. Occasional basalt gravels are present. Archaeological material is sparsely distributed within Unit NAI11. The uppermost unit NAI12 has been dated to 32.8 ± 2.2 ka (Table 2).

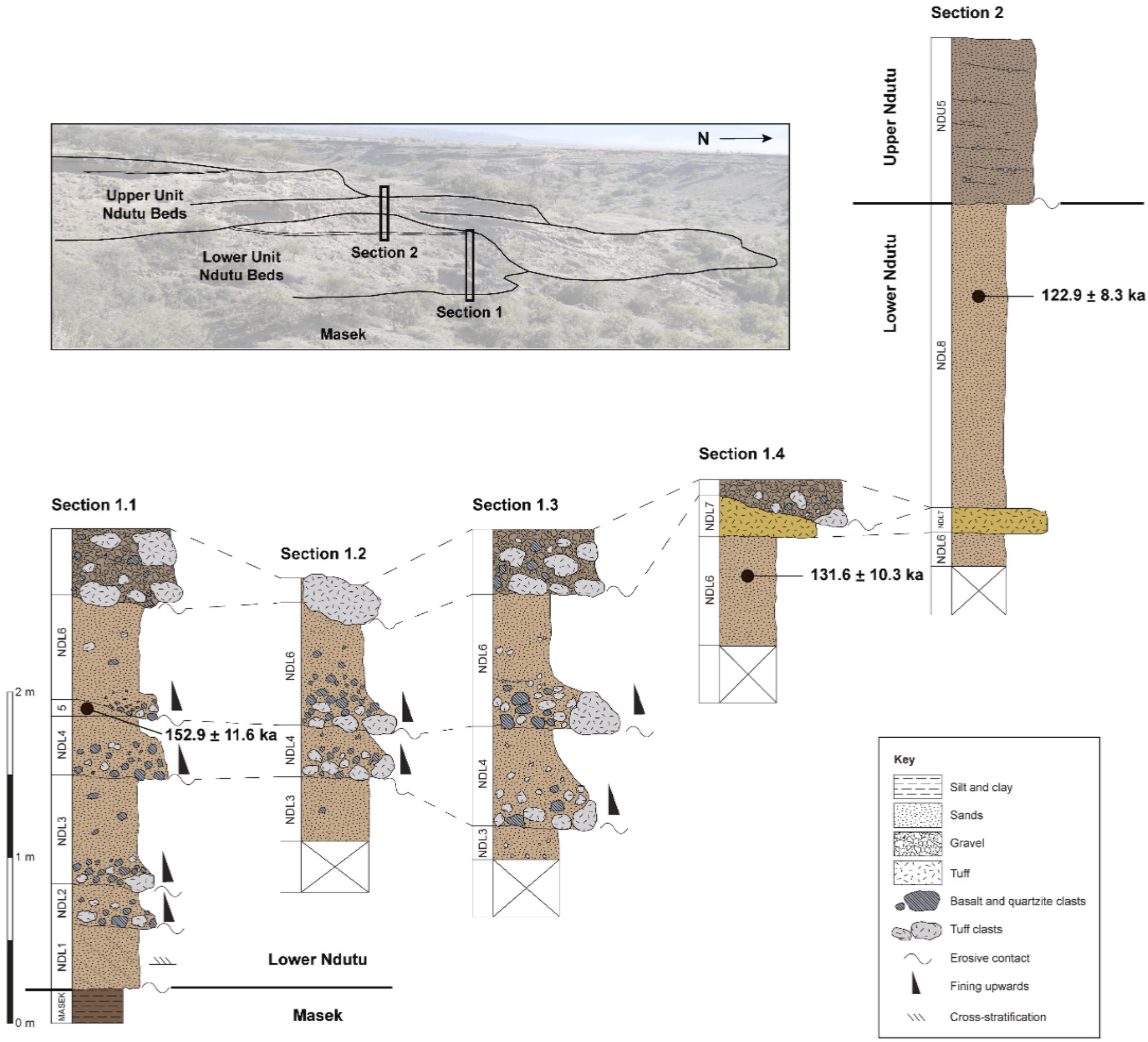

Fig. 6. Lower Ndutu stratigraphic sections at Ndutu type site.

5. Discussion

5.1. The Middle Stone Age at Olduvai Gorge

The Middle Stone Age (MSA) is an African techno-complex associated with early Homo sapiens, and is defined by the production of prepared cores—primarily Levallois and Discoid—as well as the use of lithic points, which may be hafted (e.g., Clark, 1988; McBrearty and Brooks, 2000; Barham and Mitchell, 2008; Scerri and Will, 2023). While this general definition applies broadly, significant regional variability exists across the continent. In northern Tanzania, the MSA has been subdivided into several industries, summarised in Table 6. This classification, proposed by M. Mehlman, presents several challenges, including the provenance of the assemblages (surface finds vs. excavated contexts), the antiquity of some excavations (dating back to the early 20th century), and the integration of newer collections that do not easily fit within the established framework.

The Middle Stone Age (MSA) at Olduvai Gorge is known from numerous lithic and faunal remains recovered from both surface collections and excavations (Leakey et al., 1972; Mabulla, 1990; Eren et al., 2014). The first and most significant research was led by M. Leakey and collaborators (1972), which described a collection of Levallois cores made of basalt and phonolite. Based on their characteristics, these materials were linked to assemblages from the Eyasi Lakeshore area and the Ngaloba Beds at Laetoli.

At Eyasi Lakeshore, Kohl-Larsen collected surface materials, and Domínguez-Rodrigo conducted test excavations (Mehlman, 1989; Domínguez-Rodrigo et al., 2007), identifying the so-called Njarasan industry, a variety of the Sangoan (Mehlman, 1989). The age of these assemblages is estimated at approximately 200 ka BP or older based on stratigraphic correlations (Mehlman, 1989), with some dating them to the transition between the Middle and Late Pleistocene (Domínguez-Rodrigo et al., 2007). Currently, the Leakey's MSA materials from Olduvai are unavailable, but the proposed chronology of the base of the Ndutu Beds presented here (~150 ka BP; Table 2) suggests a temporal separation between these assemblages. Additionally, there are

Table 3
Summary of the main stratigraphic and sedimentological characteristics of the units described at the Lower Ndutu type site.

Unit	Thickness	Lithology	Sedimentary Structures	Grain size/Clast type	Colour	Archaeopalaeontological content	Age
NDL1	40 cm	Sands	Cross-stratification. Erosive base.	Medium to coarse sand.	Greyish brown (10 YR 5/2)	Absent	–
NDL2	25 cm	Clast-supported conglomerate	Fining upwards sequence. Erosive base.	Very small boulders to fine gravel and sand. Polymictic: tuff, basalt and quartzite clasts. Subrounded, medium to high sphericity.	Grey (10 YR 5/1) to Greyish brown (10 YR 5/2)	Absent	–
NDL3	70 cm	Clast-supported conglomerate	Fining upwards sequence. Erosive base.	Very small boulders to fine gravel and sand. Polymictic: tuff, basalt and quartzite clasts. Subrounded, medium to high sphericity.	Grey (10 YR 5/1) to Greyish brown (10 YR 5/2)	Absent	–
NDL4	40 cm	Clast-supported conglomerate	Fining upwards sequence. Erosive base.	Very small boulders to fine gravel and sand. Polymictic: tuff, basalt and quartzite clasts. Subrounded, medium to high sphericity.	Grey (10 YR 5/1) to Greyish brown (10 YR 5/2)	Absent	–
NDL5	<15 cm	Clast-supported conglomerate	Fining upwards sequence. Erosive base.	Fine gravel to sand. Polymictic: tuff, basalt and quartzite clasts. Subrounded, medium to high sphericity.	Grey (10 YR 5/1) to Greyish brown (10 YR 5/2)	Absent	152.9 ± 11.6 ka
NDL6	70 cm	Clast-supported conglomerate	Fining upwards sequence. Erosive base.	Very small boulders to fine gravel and sand. Polymictic: tuff, basalt and quartzite clasts. Subrounded, medium to high sphericity.	Grey (10 YR 5/1) to Greyish brown (10 YR 5/2)	Absent	131.6 ± 10.3 ka
NDL7	25 cm	Marker tuff	Massive.	Medium-grained trachytic vitric tuff.	White (10 YR 8/2)	Absent	–
NDL8	1.8 m	Tuffaceous silt	Massive.	Silt to very fine sand.	Very pale brown (10 YR 7/3)	Absent	122.9 ± 8.3 ka

clear differences from a technological perspective, particularly the absence of heavy-duty tools.

The Olduvai MSA assemblages have also been associated with Ngaloba at Laetoli, where a skull (LH 18) classified as an archaic *Homo sapiens* was discovered (Day et al., 1980). The cultural correlation was based on the presence of a marker tuff shared by both sites, dated to 120 ka BP (Hay, 1987). Several researchers have attempted to date the Ngaloba Beds. Radiometric dating associated with LH 18 places them between 129 and 108 ka BP (Hay, 1987), while Manega and Deino's estimates suggest an age range of 200–240 ka BP (Manega, 1993; Deino et al., 2021).

Given these data, the proposed chronology of the marker tuff and the 108–129 ka BP dates obtained by Hay (1987) align with our dates for the uppermost section of the Lower Ndutu Unit (~120 ka BP; Table 2), potentially allowing for the correlation of these assemblages. However, we cannot directly associate the Olduvai assemblages with those from Ngaloba for several reasons. Firstly, both the Ngaloba and Olduvai assemblages were recovered from surface contexts (Leakey et al., 1972; Mabulla, 2015; Masao and Kimambo, 2022). In the case of Olduvai, the assemblage was collected from two different locations, and its exact stratigraphic position within the Ndutu Beds is unknown. Secondly, from a techno-typological perspective, the Ngaloba assemblage is characterised by the presence of heavy-duty tools and points, which are absent from Leakey's collection and nearly absent among the 72 find-spots identified by Eren and his team (2014).

Presently, there are only two stratified and dated MSA sites at Olduvai Gorge located outside the type locality: DGS and VCS, located at the junction of the Main and Side Gorges (Maíllo-Fernández, 2019a, 2022), approximately 5 km west of the Ndutu type site (Loc. 26). VCS is a multi-level fluvial site with very few lithic artefacts, yet it is clearly MSA and contains faunal remains without evidence of anthropogenic modification (Maíllo-Fernández et al., 2019a). In contrast, DGS, situated 400 m north of VCS, has a single but rich archaeological level with abundant lithic and faunal remains (Maíllo-Fernández et al., 2022). The lithic industry is dominated by Discoidal and Levallois reduction strategies, with few retouched tools and an absence of points (Solano-Megías et al., 2025). Faunal remains include Equidae, Hippotragini, and Alcelaphini, though very few have been taxonomically identified. Unlike VCS, DGS does show evidence of anthropogenic modification on the faunal remains (Maíllo-Fernández et al., 2022).

The two Olduvai MSA sites are chronologically placed between 75 and 86 ka BP, situating them within the proposed age range of the Kisele industry, the local MSA industry, which spans from 108 ka BP to 50 ka BP (Mehlman, 1989; Bushozi et al., 2020; Martín-Perea et al., 2020). This industry is characterised by Discoidal and Levallois flaking and the presence of both unifacial and bifacial points (Mehlman, 1989). However, the two Olduvai assemblages do not fit neatly within the Kisele techno-typological framework (Maíllo-Fernández et al., 2022; Solano-Megías et al., 2025). The differences may be due to multiple factors, including technological traditions or, more plausibly, functional differences in site activities.

A similar case is found at the open-air site of Loiyangalani, located in the Serengeti and dated to 64 ± 4.4 ka BP during Marine Isotope Stage (MIS) 4 (Bower et al., 1985; 2012). This MSA site, interpreted as a primary butchery location (Masele, 2020), differs from both Olduvai and Kisele industries in its high percentage of bipolar débitage and the abundance of sidescrapers among the tools (Maíllo-Fernández et al., 2019b).

Thus, current evidence suggests that MSA occupations at Olduvai Gorge are concentrated toward the end of MIS 5 and the beginning of MIS 4. However, they do not fit well within the established MSA industrial frameworks of northern Tanzania (Mehlman, 1989), indicating potential technological variability among these groups and their adaptations to different environmental conditions. Additionally, based on surface evidence (Mabulla, 1990; Eren et al., 2014), we cannot rule out the presence of older or more recent MSA occupations at Olduvai Gorge, potentially dating between 150 and 70 ka BP. However, no direct archaeological evidence has yet been identified.

5.2. *The Later Stone Age at Olduvai Gorge*

The Naisiusiu Type Site has been the reference point for the Later Stone Age (LSA) at Olduvai Gorge (Leakey et al., 1972). The site was first discovered by L. Leakey in 1931 when he collected surface material. Decades later, in 1969, M. Leakey collected another surface assemblage and conducted a small test excavation. The studied materials, which

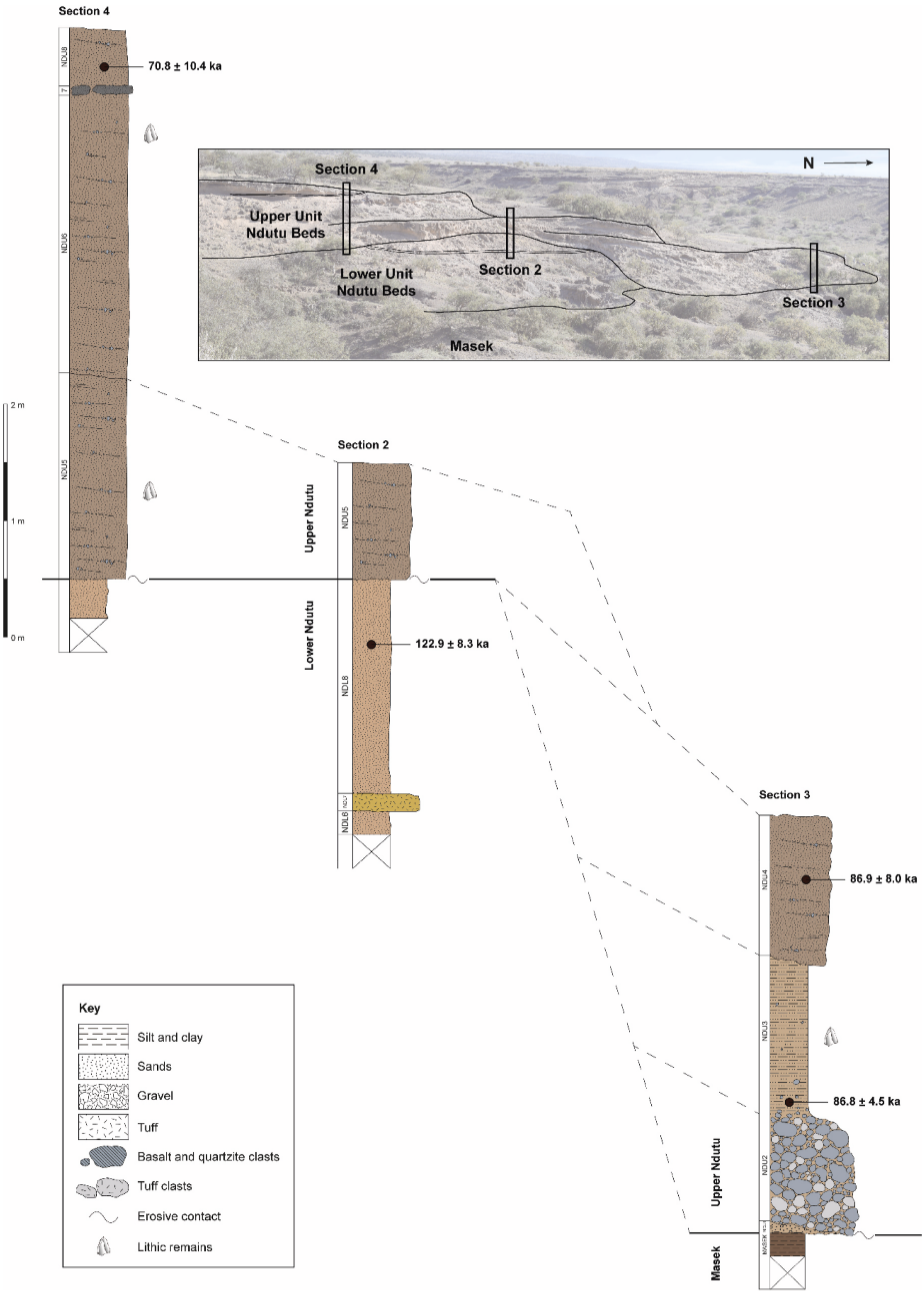

Fig. 7. Upper Ndutu stratigraphic sections at Ndutu type site.

Table 4
Summary of the main stratigraphic and sedimentological characteristics of the units described at the Upper Ndutu type site.

Unit	Thickness	Lithology	Sedimentary Structures	Grain size/Clast type	Colour	Archaeopalaeontological content	Age
NDU1	<10 cm	Clast-supported conglomerate	Erosive base.	Fine to medium gravel. Rounded, spherical basalt and quartz clasts.	Grey (10 YR 6/1)	Absent	–
NDU2	0.9–1 m	Clast-supported conglomerate	Massive. Erosive base.	Heterolithic. Medium to very coarse gravel, some small boulders. Polymictic: mainly basalt and quartzite, some tuff and phonolite. Scarce sandy matrix.	Grey (10 YR 6/1)	Absent	–
NDU3	1.4 m	Silts and sands	Massive.	Silt to very fine sand.	Very pale brown (10 YR 7/3)	MSA lithic remains	86.8 ± 4.5 ka
NDU4	1.2 m	Sandstone	Some biotite laminae and coarser passings.	Medium to coarse sand.	Light brownish grey (10 YR 6/2)	MSA lithic remains	86.9 ± 8.0 ka
NDU5	1.7 m	Sandstone	Some biotite laminae and coarser passings.	Medium to coarse sand.	Light brownish grey (10 YR 6/2)	MSA lithic remains	–
NDU6	2.5 m	Sandstone	Some biotite laminae and coarser passings.	Medium to coarse sand.	Light brownish grey (10 YR 6/2)	MSA lithic remains	–
NDU7	<10 cm	Biotite-rich sandstone	Massive.	Medium to coarse sand. Biotite abundant.	Very dark grey (10 YR 3/1)	Absent	–
NDU8	40 cm	Sandstone	Massive.	Medium to coarse sand.	Light brownish grey (10 YR 6/2)	MSA lithic remains	70.8 ± 10.4 ka

included many blades, bladelets, and crescents among the retouched pieces, clearly indicate their association with the LSA (Leakey et al., 1972). In 2016, a new test excavation was conducted in the area, though its exact location was not specified and the recovered materials were primarily made of Naibor quartz, with bipolar knapping being predominant (Mora et al., 2020). This technological pattern is entirely different from what had previously been known.

As with the Ndutu Beds, multiple dating attempts have been made for the Naisiusiu Beds. Most of these efforts aimed to establish the chronology of the Naisiusiu type site; however, in many cases, the dated samples were not recovered *in situ*, but rather collected from slope wash or eroded contexts adjacent to the exposure, limiting their direct association with the stratified sequence. The first dates placed the archaeological level at 17.5 ka uncal BP using radiocarbon (^{14}C) dating (Hay, 1976). Manega (1993) later estimated its age at ~42 ka BP, while Skinner and collaborators produced a broader range between 62 and 39 ka BP (Skinner et al., 2003), though these dates were based on surface samples and one taken far from the site. More recently, Smedley et al. (2024) tentatively placed the Naisiusiu Beds between 23 and 12 ka BP.

In her work on Naisiusiu, Leakey et al. (1972) identified two archaeological levels, one of which was particularly rich in faunal and lithic remains. Our archaeological work at Naisiusiu has confirmed the presence of both levels and revealed that archaeological materials, albeit in lower densities, are distributed throughout the entire stratigraphic sequence of the type site. Of the three OSL samples taken, two were taken from above and below the archaeological levels identified by Leakey et al. (1972). Our results place the densest archaeological levels, in Units NAI4 and NAI6 (Fig. 8), within a time frame between 45 and 65 ka BP (Table 2).

5.3. Regional context and correlations

The transition from MSA to LSA in northern Tanzania has been proposed based on the systematic use of bipolar methods on anvil and blade/bladelet laminates (Mehlman, 1989; Díez-Martín et al., 2009a,b; Solano-Megías et al., 2021). Once again, M. Mehlman proposed the chrono-cultural framework for this region, which is summarised in Table 6. At the regional level, the Naisiusiu industry has been linked to the Lemuta industry of Nasera (Levels 4 and 5), located 30 km north of Olduvai (Mehlman, 1989). Lemuta industry is clearly LSA, where the production of blades/bladelets and crescents predominates as the most characteristic tool (Mehlman, 1989). The connection between Lemuta and Naisiusiu was based on two main arguments. The first was chronological synchronicity: the initial radiocarbon dates for Naisiusiu were 16 ka uncal BP, while the Lemuta industry at Nasera was dated between 17 and 21 ka uncal BP (Mehlman, 1989). However, more recent dating indicates a minimum age of 50 ka uncal BP for Lemuta, and it is still associated with Naisiusiu, now with a greater antiquity (Ranhorn and Tryon, 2018). Our team has dated both sites, yielding an OSL date of 47.1 ± 4.5 ka BP for Level 5 (Lemuta) at Nasera (Martín-Perea et al., 2020) and a range of 45.3–65.3 ka BP for Naisiusiu. Therefore, from a chronological perspective, Naisiusiu and Lemuta could still be correlated. A second basis for this correlation comes from technotypological comparisons of both lithic assemblages. Both collections contain geometric microliths, particularly trapezoidal and crescent-shaped tools (Mehlman, 1989).

The chronology proposed in this study for the Naisiusiu type site reinforces the idea of an early onset of the LSA in this region. The beginning of the LSA has been suggested to occur at ~60 ka BP in Unit V of Mumba, Tanzania (Gliganic et al., 2012), around 67 ka BP at Panga ya Saidi, and 46 ka BP at Enkapune ya Muto, both in Kenya (Ambrose, 1998; Shipton et al., 2018). However, this transition to the LSA was not culturally uniform and followed a mosaic pattern (Tryon, 2019).

For instance, at Enkapune ya Muto, the LSA is characterised by the appearance of geometric backed pieces, whereas at Mumba V, it is marked by an increased use of the bipolar technique. A similar scenario is observed in Nasera Levels 8/9–11, where the bipolar technique is also associated with blade and bladelet debitage (Solano-Megías et al., 2021). Finally, the use of ochre, ostrich eggshells, and marine shells marks the beginning of the LSA at sites such as Mumba V, Kisese II (Tanzania), and Panga ya Saidi (Mehlman, 1989; Díez-Martín et al., 2009a,b; Tryon, 2019; Shipton et al., 2022), but it is absent in Nasera and Naisiusiu.

Regardless of the specific cultural pathways, it is evident that the MSA-LSA transition occurred relatively quickly in northern Tanzania (Table 6). Between the end of the MSA, marked by Nasera Level 12 at ~50 ka BP (Martín-Perea et al., 2020), and the establishment of the Lemuta industry at Nasera Levels 4 and 5 and the Naisiusiu type site at ~45 ka BP, a sequence of occupations fills the gap. These include the Nasera Levels 8–11, classified as Early Later Stone Age (Solano-Megías et al., 2021), and the Nasera industry at Levels 6 and 7 (Mehlman, 1989). In other words, the Later Stone Age was fully established in just

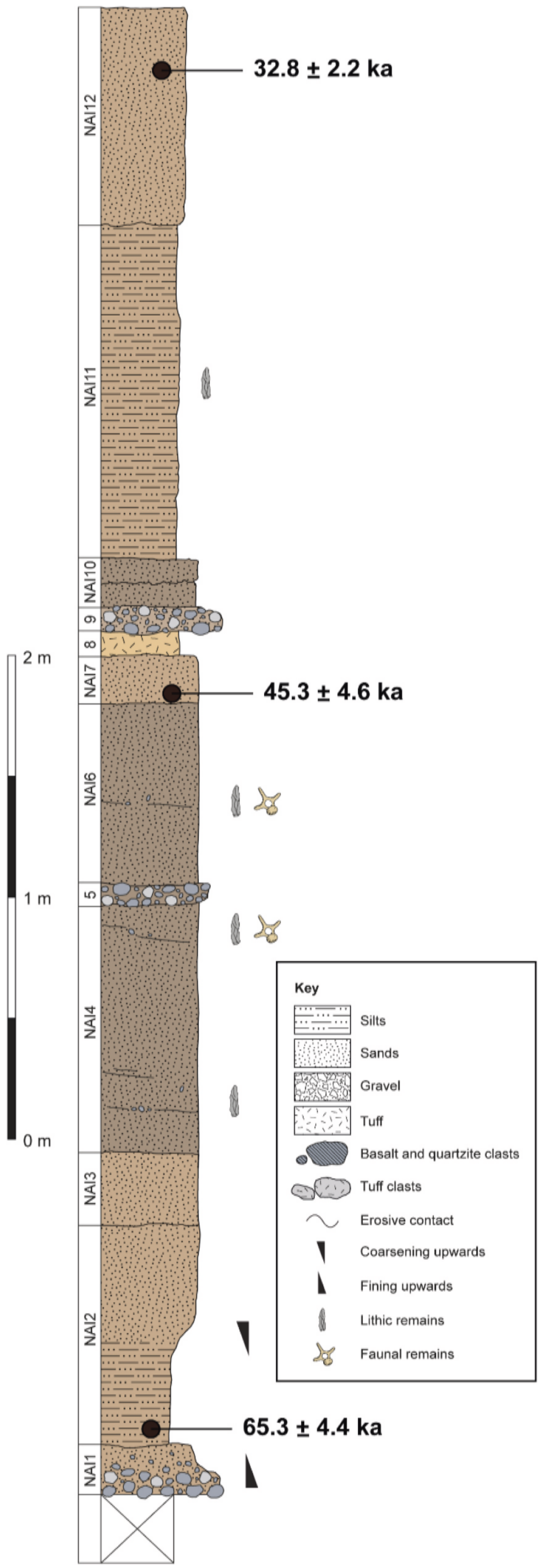

Fig. 8. Naisiusiu type site stratigraphic section.

five millennia.

6. Conclusions

This study presents new geological and chronometric data from the type localities of the Ndutu and Naisiusiu Beds at Olduvai Gorge. Through detailed stratigraphic profiling and optically stimulated luminescence (OSL) dating, we refine the depositional history and archaeological potential of these key units, which are critical for understanding the Middle and Later Stone Age record in northern Tanzania.

The Lower Ndutu sequence, disconformably overlying the Masek Beds, consists of stacked fining-upward conglomerate-to-sand sequences capped by a distinctive white trachytic marker tuff and a thick tuffaceous silt. New OSL dates place the deposition of this sequence between 152.9 ± 11.6 ka and 122.9 ± 8.3 ka. These results extend the known age range for the Lower Ndutu Unit and provide a refined geochronological framework for early Middle Stone Age occupations in the gorge.

The Upper Ndutu Beds overlie both the Masek and Lower Ndutu units across an erosional unconformity. The sequence begins with polymictic conglomerates and transitions into sandy and silty deposits, some of which are archaeologically rich. Multiple cemented sandstone units dominate the upper part of the sequence, including the regionally traceable biotite-rich marker bed. OSL dates place this unit between 86.8 ± 4.5 ka and 70.8 ± 10.4 ka.

At the Naisiusiu type site, the sequence comprises basal fluvial gravels, a middle subunit of sheetwash tuffaceous sands, and an upper subunit of aeolian silts. Archaeological materials were recovered from multiple stratigraphic levels. New OSL dates place the sequence between 65.3 ± 4.4 ka and 32.8 ± 2.2 ka, confirming a much earlier onset for the Later Stone Age in this region than previously assumed. These dates allow for direct correlation with the Lemuta industry at Nasera and support the presence of purely LSA traits by at least ~45 ka BP.

Our findings revise the chronological framework for the Ndutu and Naisiusiu Beds. The new age ranges confirm that Olduvai Gorge hosted sustained hominin occupation during critical phases of behavioural and technological change. They also reinforce the need for further stratified excavations and chronometric sampling, particularly in the poorly resolved transition between the MSA and LSA, which our study suggests occurred over a relatively brief period between 50 and 45 ka BP.

Author contributions

All authors contributed substantially to the manuscript and approved its final version. DMMP, AM, JM, NA, ISM, and JMMF were responsible for conception, study design, execution, data acquisition, analysis, and interpretation. DMMP, AM, JM, NA, ISM, CA, ARH, DU, XA, AG, AM, and JMMF drafted or wrote, substantially revised or critically reviewed the article.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly and OpenAI ChatGPT with caution to improve language and readability. After using these tools and services, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

Declaration of competing interest

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

Table 5
Summary of the main stratigraphic and sedimentological characteristics of the units described at the Naisiusiu type locality.

Unit	Thickness	Lithology	Sedimentary Structures	Grain size/Clast type	Colour	Archaeopalaeontological content	Age
NAI1	>20 cm	Clast-supported conglomerate	Fining-upward sequence.	Coarse to fine gravel to fine augitic sand. Rounded, spherical basalt and quartzite clasts.	Grey (10 YR 6/1)	Absent	–
NAI2	90 cm	Silts and sands	Coarsening-upward sequence.	Silt to fine sand.	Light brownish grey (10 YR 6/2)	Absent	65.3 ± 4.4 ka
NAI3	30 cm	Sands with lapilli	Massive.	Medium sand.	Light brownish grey (10 YR 6/2)	Absent	–
NAI4	1 m	Tuffaceous sands	Massive, some coarser laminae.	Fine to medium sand.	Light grey (10 YR 7/2)	LSA lithic remains, faunal remains	–
NAI5	<10 cm	Matrix-supported conglomerate	Massive.	Very fine to fine gravel. Basalt and tuff.	Light grey (10 YR 7/2)	Absent	–
NAI6	75 cm	Tuffaceous sands	Massive, some coarser laminae.	Fine to medium sand.	Light grey (10 YR 7/2)	LSA lithic remains, faunal remains	–
NAI7	20 cm	Sands	Well sorted.	Medium sand.	Light brownish grey (10 YR 6/2)	Absent	45.3 ± 4.6 ka
NAI8	<10 cm	Marker tuff	Massive.	Fine to medium-grained phonolitic tuff.	Pale yellow (2.5 YR 8/4) to Very pale brown (10 YR 8/3)	Absent	–
NAI9	10 cm	Matrix-supported conglomerate	Massive.	Medium to coarse gravel. Basalt and tuff.	Light grey (10 YR 7/2)	Absent	–
NAI10	<20 cm	Tuffaceous sands	Laminated.	Fine to medium sand.	Light grey (10 YR 7/2)	Absent	–
NAI11	1.4 m	Tuffaceous silts	Massive.	Silt. Scarce basalt gravels.	Very pale brown (10 YR 7/3)	LSA lithic remains, faunal remains	32.8 ± 2.2 ka
NAI12	90 cm	Tuffaceous silts and sands	Massive.	Silt to very fine sand. Scarce basalt gravels.	Light brownish grey (10 YR 6/2)	Absent	–

Table 6
Northern Tanzania MSA-LSA sites and industries cited in the text. *Survey assemblage. Raw materials: B (basalt), Q (quartz), QZ (quartzite), C (chert).

Technocomplex	Industry	Site	Raw Material	Technology	% retouched	Typology	Chronology (ka)	Reference
MSA	Njarasan	Eyasi Shore	91.2 (B)	Discoid	4.7	Heavy duty, Scrapers	±200	Mehlman, 1989
	Ngaloban	Laetoli	61 (B)	Discoid	36.6*	Scrapers, heavy duty, points (uni/bifacial)	100–240	Hay (1987), Manega (1993), Mabulla (2015)
	Sanzako	Mumba VI-B	77.9 (Q)	Discoid	10.5	Scrapers, bifacial pieces, heavy duty	131–109	Mehlman (1989)
	Kisele	Mumba VIA upper	74.7 (Q)	Discoid, Levallois	13.9	Scrapers, Points (uni/bifacial)	63–73	Mehlman (1989), Bushozi et al., (2020)
		Mumba VIA lower					93–108	
		Nasera 18-25	82.9 (Q)	Discoid, Levallois	5.2	Scrapers, points		Mehlman (1989)
		Nasera 12-17	78.2 (Q)	Discoid	7.1	Scrapers, points	50–61	Mehlman (1989), Martín-Perea et al., (2020)
	–	VCS (Olduvai)	56 (QZ)	Discoid, Levallois	8	Sidescrapers	86–75	Maíllo-Fernández et al. (2019a)
	Loiyangalanian	Loiyangalani	60.5 (QZ)	Discoid, Bipolar	21.4	Sidecrapers, denticulates	64	Bower et al. (2012), Maíllo-Fernández et al., (2019b)
	–	DGS (Olduvai)	68.9 (QZ)	Discoid	3.4	Retouched pieces Denticulates	86–75	Maíllo-Fernández et al. (2022)
LSA	Mumba	Nasera 8/9	50 (Q)	Bipolar/ Laminar		Backed pieces	<50	Solano-Megías eta l. (2021)
		Nasera 10	48.7 (Q)	Bipolar/ laminar		Notch/point	<50	Solano-Megías eta l. (2021)
		Nasera 11	35.4 (Q)	Bipolar/ Laminar		Sidescraper	<50	Solano-Megías eta l. (2021)
		Mumba V upper	N/A (Q)	Bipolar	2.2	Backed pieces	49.1	Gliganic et al., (2012); Díez-Martín et al., 2009a,b
		Mumba V middle	N/A (Q)	Bipolar	0.4	Backed pieces	51.3	Gliganic et al., (2012); Díez-Martín et al., 2009a,b
		Mumba V lower	N/A (Q)	Bipolar	1.6	Backed pieces/ sidescraper	56.9	Gliganic et al., (2012); Díez-Martín et al., 2009a,b
	Nasera	Nasera 6/7	95 (Q)	Bipolar	3.5	Sidescraper/Points	>47-<50	Mehlman (1989); Martín-Perea et al. (2020)
		Mumba Lower III	86.9 (Q)	Discoid/ Levallois	5.5	Sidescraper	36.8	Mehlman (1989); Gliganic et al. (2012)
	Lemuta	Nasera 5/4	87.7 (Q)	Single platform/ Bipolar	3.1	Sidescraper/backed pieces	47.1	Mehlman (1989); Martín-Perea et al. (2020)
		Naisiusiu (Olduvai)	74.6 (C)	Blade/ bladelets	6.6	Backed pieces	45.3–65.3	Leakey et al. (1972)
	Sisale	Nasera 3b	94.6	Bipolar/single platform	5.2	Backed pieces	11.4	Mehlman (1989); Ranhorn and Tryon (2018)

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Data availability

All data and/or code is contained within the submission.

References

Ambrose, S.H., 1998. Chronology of the later stone age and food production in East Africa. J. Archaeol. Sci. 25 (4), 377–392.

Ashley, G.M., 2007. Orbital rhythms, monsoons, and playa lake response, Olduvai Basin, equatorial East Africa (ca. 1.85-1.74 Ma). Geology 35, 1091–1094.

Ashley, G.M., Hay, R.L., 2002. Sedimentation patterns in a Plio-Pleistocene volcaniclastic rift-platform basin, Olduvai gorge, Tanzania. In: Sedimentation in Continental Rifts, vol. 73. SEPM Special Publication, pp. 107–122.

Barham, L., Mitchell, P., 2008. The First Africans. African Archaeology from the Earliest Toolmakers to Most Recent Foragers. Cambridge University Press, Cambridge.

Bello-Alonso, P., Ríos-Garaizar, J., Panera, J., Rubio-Jara, S., Pérez-González, A., Rojas, R., Baquedano, E., Mabulla, A., Domínguez-Rodrigo, M., Santonja, M., 2021. The first comprehensive micro use-wear análisis of an early Acheulean assemblage (Thiongo Korongo, Olduvai gorge, Tanzania). Quat. Sci. Rev. 263, 106980.

Blumenschine, R.J., Peters, C.R., Masao, F.T., Clarke, R.J., Deino, A.L., Hay, R.L., Swisher, C.C., Stanistreet, I.G., Ashley, G.M., McHenry, L.J., Sikes, N.E., 2003. Late Pliocene *Homo* and hominid land use from western Olduvai Gorge, Tanzania. Science 299 (5610), 1217–1221.

Blumenschine, R.J., Stanistreet, I.G., Njau, J.K., Bamford, M.K., Masao, F.T., Albert, R. M., Stollhofen, H., Andrews, P., Prassack, K.A., McHenry, L.J., Fernández-Jalvo, Y., Camilli, E.L., Ebert, J.I., 2012. Environments and hominin activities across the FLK Peninsula during *Zinjanthropus* times (1.84 Ma), Olduvai gorge, Tanzania. J. Hum. Evol. 63, 364–383.

Bower, J.R.F., Gifford, D., Livingstone, D., 1985. Excavations at the Loiyangalani site, Serengeti National Park, Tanzania. National Geographic Society Research Reports (1979 projects) 20, 41–56.

Bower, J.R.F., Mabulla, A.Z.P., Kobusiewicz, M., 2012. Loiyangalani: a cultural isolate in the middle stone age of northern Tanzania. Studies in African Archaeology 11, 479–491.

Bushozi, P.M., Skinner, A., de Luque, L., 2020. The middle stone age (MSA) technological patterns, innovations, and behavioral changes at bed VIA of Mumba rockshelter, northern Tanzania. Afr. Archaeol. Rev. 37, 293–310.

Buylaert, J.P., Murray, A., Thomsen, K., Jain, M., 2009. Testing the potential of an elevated temperature IRSL signal from K-feldspar. Radiat. Meas. 44, 560–565.

Cerling, T.E., Hay, R.L., 1986. An isotopic study of palaeosol carbonates from Olduvai Gorge. Quat. Res. 25, 63–78.

Clark, J.D., 1988. The middle stone age of East Africa and the beginnings or regional identity. J. World PreHistory 2 (3), 235–305.

Colarossi, D., Duller, G.A.T., Roberts, H.M., 2018. Exploring the behaviour of luminescence signals from feldspars: implications for the single aliquot regenerative dose protocol. Radiat. Meas. 109, 35–44.

Day, M.H., Leakey, M.D., Magori, C., 1980. A new hominid fossil skull (LH 18) from the Ngaloba Beds, Laetoli, northern Tanzania. Nature 284, 55–56.

De la Torre, I., Benito-Calvo, A., Martín-Ramos, C., McHenry, L., Mora, R., Njau, J.K., Pante, M.C., Stanistreet, I.G., Stollhofen, H., 2021. New excavations in the MNK skull site, and the last appearance of the Oldowan and *Homo habilis* at Olduvai gorge, Tanzania. J. Anthropol. Archaeol. 61, 101255.

De la Torre, I., Doyon, L., Benito-Calvo, A., Mora, R., Mwakyoma, I., Njau, J.K., Peters, R. F., Theodoropoulou, A., d'Errico, F., 2025. Systematic bone tool production at 1.5 million years ago. Nature 640, 130–134.

Deino, A.L., Heil, Jr. C., King, J., McHenry, L.J., Stanistreet, I.G., Stollhofen, H., Njau, H., Mwankunda, J., Schick, K.D., Toth, N., 2021. Chronostratigraphy and age modelling of Pleistocene drill cores from the Olduvai Basin, Tanzania (Olduvai gorge coring Project). Palaeogeogr. Palaeoclimatol. Palaeoecol. 571, 109990.

Díez-Martín, F., Domínguez-Rodrigo, M., Sánchez, P., Mabulla, A.Z.P., Tarriño, A., Barba, R., Prendergast, M., de Luque, L., 2009a. The Middle to Later Stone Age technological transition in East Africa. New data from Mumba rockshelter Bed V (Tanzania) and their implications for the origin of modern human behavior. J. Afr. Archaeol. 7 (2), 147–173.

Díez-Martín, F., Domínguez-Rodrigo, M., Sánchez, P., Mabulla, A.Z.P., Tarriño, A., Barba, R., Prendergast, M., de Luque, L., 2009b. The Middle to Later Stone Age technological transition in East Africa. New data from Mumba rockshelter Bed V (Tanzania) and their implications for the origin of modern human behavior. J. Afr. Archaeol. 7 (2), 147–173.

Díez-Martín, F., Sánchez-Yustos, P., Uribelarrea, D., Baquedano, E., Mark, D.F., Mabulla, A., Fraile, C., Duque, J., Díaz, I., Pérez-González, A., Yravedra, J., Egeland, C.P., Organista, E., Domínguez-Rodrigo, M., 2015. The origino f the Acheulean: the 1.7 million-year-old site of FLK west, Olduvai gorge (Tanzania). Sci. Rep. 5, 17839.

Díez-Martín, F., Wynn, T., Sánchez-Yustos, P., Duque, J., Fraile, C., de Francisco, S., Uribelarrea, D., Mabulla, A.Z.P., Baquedano, E., Domínguez-Rodrigo, M., 2019. A faltering origin for the Acheulean? Technological and cognitive implications from FLK West (Olduvai gorge, Tanzania). Quat. Int. 526, 49–66.

Domínguez-Rodrigo, M., Díez-Martín, F., Mabulla, A., Luque, L., Alcalá, L., Tarriño, A., López-Sanz, J.A., Barba, R., Bushozi, P., 2007. The archaeology of the middle Pleistocene deposits of lake Eyasi (Tanzania). J. Afr. Archaeol. 5 (1), 47–78.

Domínguez-Rodrigo, M., Bunn, H., Mabulla, A.Z.P., Ashley, G.M., Díez-Martín, F., Barboni, D., Prendergast, M.E., Yravedra, J., Barba, R., Sánchez, A., Baquedano, E., Pickering, T.R., 2010. New excavations at the FLK *Zinjanthropus* site and its surrounding landscape and their behavioral implications. Quat. Res. 74, 315–332.

Domínguez-Rodrigo, M., Pickering, T.R., Baquedano, E., Mabulla, A.Z.P., Mark, D.F., Musiba, C., Bunn, H.T., Uribelarrea, D., Smith, V., Díez-Martín, F., Pérez-González, A., Sánchez, P., Santonja, M., Barboni, D., Gidna, A., Ashely, G., Yravedra, J., Heaton, J.L., Arriaza, M.C., 2013. First partial skeleton of a 1.34-million-year-old *Paranthropus boisei* from Bed II, Olduvai gorge, Tanzania. PLoS One 8 (12), e80347.

Domínguez-Rodrigo, M., Pickering, T.R., Almécija, S., Heaton, J.L., Baquedano, E., Mabulla, A., Uribelarrea, D., 2015. Earliest modern human-like hand bone from a new >1.84-million-year-old site at Olduvai in Tanzania. Nat. Commun. 6 (1), 7987.

Durcan, J.A., King, G.E., Duller, G.A.T., 2015. DRAC: dose rate and age calculator for trapped charge dating. Quat. Geochronol. 28, 54–61.

Eren, M., Durant, M.E., Prendergast, M., Mabulla, A.Z.P., 2014. Middle stone age archaeology at Olduvai gorge, Tanzania. Quat. Int. 322–323, 292–313.

Gaar, D., Lowick, S.E., Preusser, F., 2014. Performance of different luminescence approaches for the dating of known-age glaciofluvial deposits from northern Switzerland. Geochronometria 41 (1), 65–80. https://doi.org/10.2478/s13386-013-0139-0.

Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H., Olley, J.M., 1999. Optical dating of single and multiple grains of quartz from Jinmium rock shelter, Northern Australia: part 1, experimental design and statistical models. Archaeometry 41, 339–364.

Gliganic, L.A., Jacobs, Z., Roberts, R.G., Domínguez-Rodrigo, M., Mabulla, A.Z.P., 2012. New ages for Middle and Later Stone Age deposits at Mumba rockshelter, Tanzania: optically stimulated luminescence dating of quartz and feldspar grains. J. Hum. Evol. 62 (4), 533–547.

Hay, R.L., 1976. The Geology of Olduvai Gorge. University of California Press, Berkeley.

Hay, R.L., 1987. Geology of the Laetoli area. In: Leakey, M.D., Harris, J.M. (Eds.), Laetoli: A Pliocene Site in Northern Tanzania. Clarendon Press, Oxford, pp. 23–47.

Hay, R.L., Reeder, R.J., 1978. Calcretes of Olduvai gorge and the Ndolanya beds of northern Tanzania. Sedimentology 25, 649–673.

Leakey, L.S.B., 1959. A new fossil skull from Olduvai. Nature 184 (4685), 491–493.

Leakey, L.S.B., 1961. New finds at Olduvai gorge. Nature 189, 649–650.

Leakey, M.D., 1971. Olduvai Gorge 3: Excavations in Beds I and II, 1960-1963. Cambridge University Press, Cambridge.

Leakey, M.D., Hay, R., Thurber, D., Protsch, R., Berger, R., 1972. Stratigraphy, archaeology, and age of the Ndutu and Naisiusiu beds, Olduvai gorge, Tanzania. World Archaeol. 3, 328–341.

Liritzis, I., Stamoulis, K., Papachristodoulou, C., Ioannides, K., 2013. A re-evaluation of radiation dose-rate conversion factors. Mediterranean Archaeology and Archaeometry 13, 1–15.

Mabulla, A., 1990. Preliminary report on an archaeological survey of Ndutu beds, Olduvai Gorge, Tanzania. Nyame Akuma 33, 20–25.

Mabulla, A., 2015. Middle Pleistocene lithic industry and hominin behavior at Laetoli. African Studia 24 (1), 13–32.

MacIntyre, R.M., Mitchell, J.G., Dawson, J.B., 1974. Age of fault movements in Tanzanian sector of East African system. Nature 247, 354–356.

Maíllo-Fernández, J.M., Marín, J., Solano-Megías, I., Uribelarrea, D., Martín-Perea, D., Aramendi, J., Medialdea, A., Arteaga, C., Pernas-Hernández, M., Gidna, A., Neogi, S., Baudot, E., Narváez, E., Mabulla, A.Z.P., 2019a. Victoria Cabrera site: a middle stone age site at Olduvai gorge, Tanzania. Quat. Int. 526 (129), 154.

Maíllo-Fernández, J.M., Solano-Megías, I., Mabulla, A., Arriaza, M.C., Bower, J.F.R., 2019b. Lithic technology at Loiyangalani, a late middle stone age site in the Serengeti, Tanzania. Afr. Archaeol. Rev. 36, 291–315.

Maíllo-Fernández, J.M., Marín, J., Martín-Perea, D.M., Uribelarrea, D., Solano-Megías, I., Asiaín, R., Baquedano, E., Domínguez-Rodrigo, M., Gidna, A., Medialdea, A., Mwamakimbula, S.H., Haruni Chilonzi, D., Arteaga, C., Mabulla, A.Z.P., 2022. The Dorothy Garrod site: a new middle stone age locality in Olduvai gorge, Tanzania. Archaeol. Anthropol. Sci. 14, 177.

Manega, P., 1993. Geochronology, Geochemistry, and Isotopic Study of the Plio-Pleistocene Hominid Sites and the Ngorongoro Volcanic Highland in Northern Tanzania. University of Colorado at Boulder, Dissertation.
Martín-Perea, D.M., Maíllo-Fernández, J.M., Medialdea, A., Marín, J., Solano-Megías, I., Gidna, A., Mabulla, A.Z.P., 2020. Revisiting an old profile: an updated geoarchaeological study at Nasera Rockshelter (Tanzania). J. Quat. Sci. 35 (7), 951–960.
Masao, F.T., Kimambo, J.S., 2022. Further notes on the Ngaloba industry, a middle stone age assemblage directly associated with early Homo in the greater Laetoli, northern Tanzania. In: Fortes-Lima, C., Mtetwa, E., Schlebusch, C. (Eds.), Cultural and Biological Approaches to Uncover African Diversity. Brill, pp. 43–60.
Masele, F., 2020. Testing meat-eating by middle stone age hominins at Loiyangalani open-air site in Serengeti National Park, Tanzania. Archaeol. Anthropol. Sci. 12, 55.
McBrearty, S., Brooks, A., 2000. The revolution that wasn't: a new interpretation of the origin of modern human behavior. J. Hum. Evol. 39, 453–563.
McHenry, L.J., 2012. A revised stratigraphic framework for Olduvai Gorge Bed I based on tuff geochemistry. J. Hum. Evol. 63, 284–299.
Medialdea, A., Brill, D., King, G.E., Zander, A., López-Ramirez, M.R., Bartz, M., Brückner, H., 2022. Violet stimulated luminescence as an alternative for dating complex colluvial sediments in the Atacama Desert. Quat. Geochronol. 71, 101337.
Mehlman, M.J., 1987. Provenience, age and associations of archaic *Homo sapiens* crania from Lake Eyasi, Tanzania. J. Archaeol. Sci. 14, 133–162.
Mehlman, M.J., 1989. Late Quaternary Archaeological Sequences in Northern Tanzania. University of Illinois. Ph.D Dissertation.
Mercader, J., Akuku, P., Bovin, N., Bugumba, R., Bushozi, P., Camacho, A., Carter, T., Clarke, S., Cueva-Temprana, A., Durkin, P., Favreau, J., Fella, K., Haberle, S., Hubbard, S., Inwood, J., Itambu, M., Koromo, S., Lee, P., Mohammed, A., Mwambwiga, A., Olesilau, L., Patalano, R., Roberts, P., Rule, S., Saladie, P., Siljedal, G., Soto, M., Umbsaar, J., Petraglia, M., 2020. Earliest Olduvai hominins exploited unstable environments 2 million years ago. Nat. Commun. 12, 3.
Millard, A., 2008. A critique of the chronometric evidence for hominid fossils: I. Africa and the Near East 500-50 ka. J. Hum. Evol. 54, 848–874.
Mora, R., de la Torre, I., Benito-Calvo, A., 2020. Trabajos arqueológicos en el área de Second Fault (Olduvai, Tanzania). Proyectos Arqueológicos en el Exterior, convocatoria de 2017, Informes y Trabajos 19, 7–15.
Munsell, A.H., 1981. A Color Notation: An Illustrated System Defining All Colors and Their Relations by Measured Scales for Hue, Value and Chroma, Fourteenth Edition. Munsell Color, Baltimore.
Murray, A.S., Thomsen, K.J., Masuda, N., Buylaert, J.-P., Jain, M., 2012. Identifying well bleached quartz using the different bleaching rates of quartz and feldspar luminescence signals. Radiat. Meas. 47, 688–695.
Prescott, J.R., Hutton, J.T., 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. Radiat. Meas. 23, 497–500.
Ranhorn, K., Tryon, C.A., 2018. New radiocarbon dates from Nasera rockshelter (Tanzania): implications for studying spatial patterns in Late Pleistocene technology. J. Afr. Archaeol. 16 (2), 211–222.
Reck, H., 1914. Erste vorläuftge Mittenilung über den Fund eines fossilen Menschenskeletts aus Zentralafrika. Sitzungsberichte Ges. Naturforschendler Freunde Berlin 3, 81–95.
Rees-Jones, J., 1995. Optical dating of young sediments using fine-grain quartz. Ancient TL 13, 9–14.
Scerri, E., Will, M., 2023. The revolution that still isn't: the origins of behavioral complexity in Homo sapiens. J. Hum. Evol. 179, 103358.
Shipton, C., Roberts, P., Archer, W., Armitage, S.J., Bita, C., Blinkhorn, J., Courtney-Mustaphi, C., Crowther, A., Curtis, R., d'Errico, F., Douka, K., Faulkner, P., Groucutt, H.S., Helm, R., Herries, A.I.R., Jembe, S., Kourampas, N., Lee-Thorp, J., Marchant, R., Mercader, J., Pitarch-Marti, A., Prendergast, M., Rowson, B., Tengeza, A., Tibesasa, R., White, T.S., Petraglia, M.D., Boivin, N., 2018. 78,000-year-old record of Middle and Later Stone age innovation in an East African tropical forest. Nat. Commun. 9 (1), 1832.
Shipton, C., Blinkhorn, J., Archer, W., Kourampas, N., Roberts, P., Prendergast, M.E., Curtis, R., Herries, A.J.R., Nediema, E., Boivin, N., Petraglia, M.D., 2022. The middle to later stone age transition at Panga ya Saidi, in the tropical coastal forest of eastern Africa. J. Hum. Evol. 153, 102954.
Skinner, A.R., Hay, R.L., Masao, F., Blackwell, B.A.B., 2003. Dating the Naisiusiu beds, Olduvai gorge, by electron spin resonance. Quat. Sci. Rev. 22, 1361–1366.
Smedley, R.K., Duller, G.A.T., Pearce, N.J.G., Roberts, H.M., 2012. Determining the K-content of single-grains of feldspar for luminescence dating. Radiat. Meas. 47 (9), 790–796.
Smedley, R.K., Fenn, K., Stanistreet, I.G., Stollhofen, H., Njau, J.K., Schick, K., Toth, N., 2024. Age-depth model for uppermost Ndutu beds constrains middle stone age technology and climate-induced paleoenvironmental changes at Olduvai gorge (Tanzania). J. Hum. Evol., 103465
Solano-Megías, I., Maíllo-Fernández, J.M., Marín, J., Martín-Perea, D.M., Mabulla, A.Z. P., 2021. Lithic technology in the earliest later stone age at Nasera rockshelter (Tanzania). Lithic Technol. 46 (1), 60–79.
Solano-Megías, I., Maíllo-Fernández, J.M., Marín, J., Martín-Perea, D.M., Mabulla, A.Z. P., 2025. Exploring the middle stone age lithic technology at DGS, Olduvai gorge, Tanzania. Archaeol. Anthropol. Sci. 17, 36.
Stanistreet, I.G., Stollhofen, H., Deino, A., McHenry, L., Toth, N., Schick, K., Njau, J.K., 2020. New Olduvai Basin stratigraphy and stratigraphic concepts revealed by OGCP cores into the Palaeolake Olduvai depocentre, Tanzania. Palaeogeogr. Palaeoclimatol. Palaeoecol. 554, 109751.
Thomsen, K.J., Murray, A.S., Jain, M., Botter-Jensen, L., 2008. Laboratory fading rates of various luminescence signals from feldspar-rich sediment extracts. Radiat. Meas. 43, 1474–1486.
Tryon, Ch A., 2019. The middle/later stone age transition and cultural dynamics of late Pleistocene East Africa. Evol. Anthropol. 28 (2), 67–282.
Blott, S.J., Pye, K., 2012. Particle size scales and classification of sediment types based on particle size distributions: Review and recommended procedures. Sedimentology 59 (7), 2071–2096.