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3.3-million-year-old stone tools from Lomekwi 3, West Turkana, Kenya

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Human evolutionary scholars have long supposed that the earliest stone tools were made by the genus *Homo* and that this technological development was directly linked to climate change and the spread of savannah grasslands. New fieldwork in West Turkana, Kenya, has identified evidence of much earlier hominin technological behaviour. We report the discovery of Lomekwi 3, a 3.3-million-year-old archaeological site where *in situ* stone artefacts occur in spatiotemporal association with Pliocene hominin fossils in a wooded palaeoenvironment. The Lomekwi 3 knappers, with a developing understanding of stone's fracture properties, combined core reduction with battering activities. Given the implications of the Lomekwi 3 assemblage for models aiming to converge environmental change, hominin evolution and technological origins, we propose for it the name 'Lomekwian', which predates the Oldowan by 700,000 years and marks a new beginning to the known archaeological record.

Conventional wisdom in human evolutionary studies has assumed that the origins of hominin sharp-edged stone tool production were linked to the emergence of the genus *Homo*[1,2] in response to climate change and the spread of savannah grasslands[3,4]. In 1964, fossils looking more like later *Homo* than australopithecines were discovered at Olduvai Gorge (Tanzania) in association with the earliest known stone tool culture, the Oldowan, and so were assigned to the new species: *Homo habilis* or 'handy man'[1]. The premise was that our lineage alone took the cognitive leap of hitting stones together to strike off sharp flakes and that this was the foundation of our evolutionary success. Subsequent discoveries pushed back the date for the first Oldowan stone tools to 2.6 million years ago[5,6] (Ma) and the earliest fossils attributable to early *Homo* to only 2.4–2.3 Ma[7,8], opening up the possibility of tool manufacture by hominins other than *Homo*[9] before 2.6 Ma[10–12].

The earliest known artefacts from the sites of Gona (~2.6 Ma)[6,12], Hadar (2.36 ± 0.07 Ma[13]), and Omo (2.34 ± 0.04 Ma[14]) in Ethiopia, and especially Lokalalei 2C (2.34 ± 0.05 Ma[15]) in Kenya, demonstrate that these hominin knappers already had considerable abilities in terms of planning depth, manual dexterity and raw material selectivity[14–19]. Cut-marked bones from Dikika, Ethiopia[20], dated at 3.39 Ma, has added to speculation on pre-2.6-Ma hominin stone tool use. It has been argued that percussive activities other than knapping, such as the pounding and/or battering of plant foods or bones, could have been critical components of an even earlier, as-yet-unrecognized, stage of hominin stone tool use[21–25]. Any such artefacts may have gone unrecognized if they do not directly resemble known Oldowan lithics, occur at very low densities or were made of perishable materials[10].

In 2011, the West Turkana Archaeological Project (WTAP) began an archaeological survey and excavation in the Lomekwi Member[26] (3.44–2.53 Ma) of the Nachukui Formation (west of Lake Turkana, northern Kenya; Fig. 1) to search for evidence of early hominin lithic behaviour. Several promising surface artefact concentrations and dispersed single finds were discovered. At the Lomekwi 3 archaeological site, 28 lithic artefacts were initially found lying on the surface or within a slope deposit, and one core was uncovered *in situ*. By the close of the subsequent 2012 field season, excavation at LOM3 had reached 13 m^2, revealing an additional 18 stone tools and 11 fossils *in situ* (Extended Data Table 1) within a horizon (approximately 80 cm) of indurated sandy-granular sediments stratified in a thick bed of fine silts (Fig. 2). A further 100 lithic artefacts and 22 fossil remains were collected from the surface immediately around the site along with two artefacts from the slope deposit (Extended Data Fig. 1). These finds occur in the same geographic and chronological range as the paratype of *Kenyanthropus platyops* (KNM-WT 38350)[27], other hominin fossils generally referred to cf. *K. platyops*[28], and one unpublished hominin tooth (KNM-WT 64060) found by WTAP in 2012 (Supplementary Information, part A and Supplementary Table 1).

Geochronological and palaeoenvironmental contexts

The chronological context of LOM3 derives from correlation with the Lomekwi Member of the Nachukui Formation[26] and radiometrically dated tuffs within it[29,30], as well as from magnetostratigraphy of the site and estimated sedimentation rates. The composite type section of the Lomekwi Member, 2–5 km east of LOM3, is bracketed by the α-Tulu Bor Tuff (3.44 ± 0.02 Ma) at the base and the Lokalalei Tuff (2.53 ± 0.02 Ma) at the top[29,30]. Closer to LOM3, two new sections provide additional context. Section 1 (CSF 2011-1; ~46 m thick, located 1.44 to 1 km north of LOM3, Extended Data Fig. 2) includes

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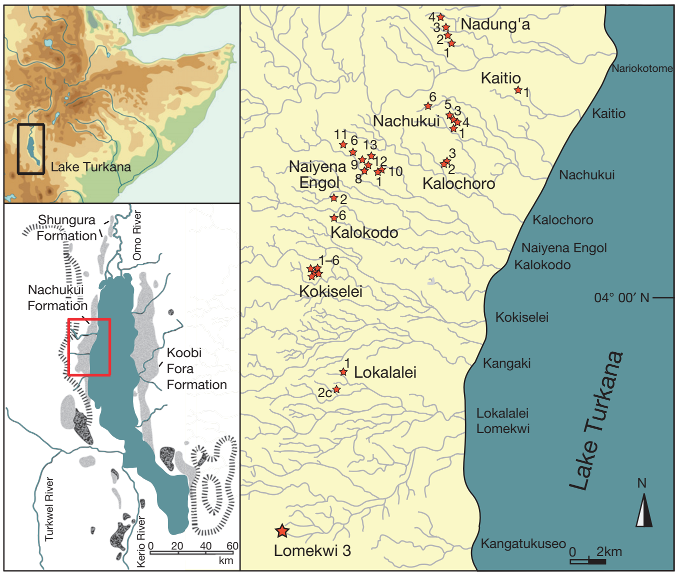

Figure 1 | Geographic location of the LOM3 site. Map showing relation of LOM3 to other West Turkana archaeological site complexes.

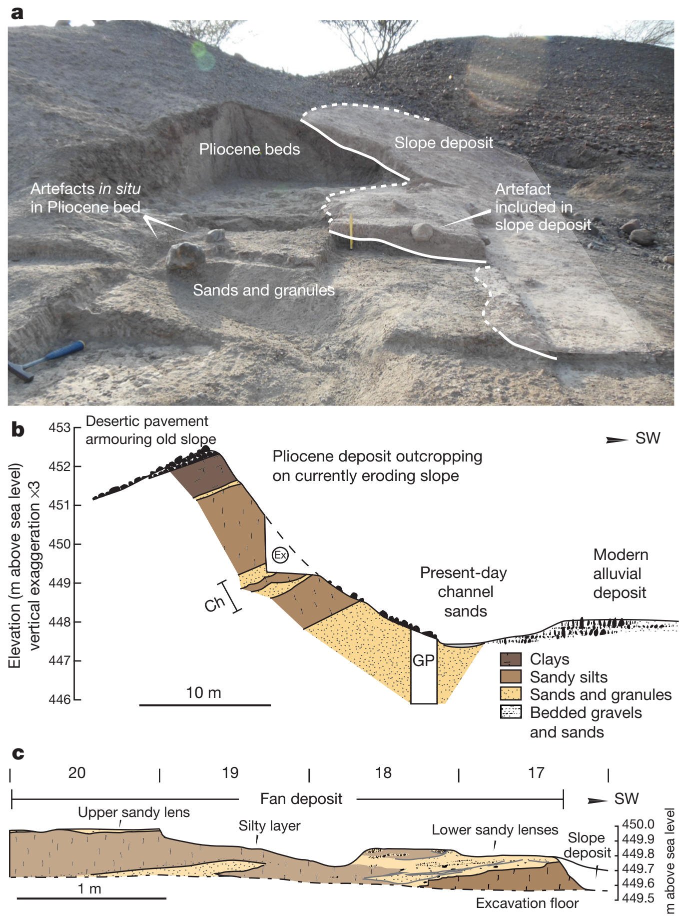

Figure 2 | LOM3 lithological context. a, View of the excavation, facing east, showing relationship between surface, slope deposit, and *in situ* contexts containing the artefacts and fossils. Scale in midground is 20 cm. Lower-leftmost artefact is the anvil LOM3-2012-K18-2, shown in Fig. 5a. **b**, Topographic profile and stratigraphic units at site level showing the excavation zone (Ex), the geological trench made at the base of the section (GP); the artefacts and fossils derive from a series of lenses of sand and granules making up a ~1 m thick bed (Ch). **c**, Section at the excavation along bands I and J (indicated by the black line in Extended Data Fig. 1a) showing the sediments which form the fan deposits containing the artefacts.

the α- and β-Tulu Bor Tuffs in the lower third (Supplementary Information, part B). Composite Section 2 (upper CSF-2012-9, ~44 m thick, located 0.4 km south of LOM3 and lower CSF-2011-2 located 0.28 km north of LOM3, Fig. 3a, b and Extended Data Fig. 2) includes at the base a lenticular tuff correlated geochemically with the Toroto Tuff in the Koobi Fora Formation where it outcrops 10–12 m above the α-Tulu Bor Tuff, and has been dated radiometrically to 3.31 ± 0.02 (refs 29, 30). Both the two Tulu Bor Tuffs in Section 1 and the Toroto Tuff in Section 2 occur in normal polarity magnetozones, corresponding to the early part of the Gauss Chron C2An (Fig. 3a and Supplementary Information, part C), while the overlying sediments at both sites are in reversed polarity zones as are the sediments encompassing the *in situ* artefacts at LOM3, 10 m above the Toroto Tuff (Fig. 3b). Thus, the artefacts were deposited after 3.31 ± 0.02 Ma during the Mammoth reverse subchron C2An.2r (3.33–3.21 Ma[31]). Based on extrapolation of sediment accumulation rates between the levels of the α-Tulu Bor and Toroto Tuffs and the onset of subchron C2An.2r, an age of 3.3 Ma is determined for LOM3 (Extended Data Fig. 3 and Supplementary Information, part C), which accords with previous interpretations of the antiquity of fossils from this locality[27–30].

Stable carbon isotopic analyses of pedogenic carbonate nodules located adjacent to and at LOM3 yielded a mean $\delta^{13}C_{VPDB}$ value of −7.3 ± 1.1‰ (Extended Data Fig. 4 and Supplementary Information, part D), which indicates a mean fraction of woody cover (f_{wc}) of 47 ± 9% and positions the site within a woodland/bushland/thicket/shrubland environment[32]. Our results are comparable to paleosol $\delta^{13}C_{VPDB}$ values of other East African hominin environments between 3.2 and 3.4 Ma but significantly woodier than the 2.6 Ma artefact site at Gona, Ethiopia (Extended Data Figs 4b, c)[32,33]. The associated fauna supports this interpretation (Supplementary Information, part E).

The Lomekwi 3 site

The LOM3 site is a low hill eroded into by a small ravine. The uppermost sediments encountered during excavation form a plaque of slope deposit which is a few centimetres thick (Fig. 2a). Under it, a series of interdigitated lenses of sands, granules and silts are found. They correspond to different facies of the same sedimentary environment related to the distal fan deposit in which the artefacts are preserved (Fig. 2c and Supplementary Information, part B). Sealed *in situ* in these Pliocene sediments (Extended Data Fig. 5), the LOM3 archaeological material is considered to be in a slightly re-distributed primary archaeological context based on the following observations: (1) artefacts of different sizes, ranging from ~1 cm wide flake fragments to very large worked cobbles and cores are present; (2) artefacts are larger and heavier than could be carried by the energy of the alluvial system that deposited the sediments (the maximal competence of the transport flow can be inferred by the coarsest fraction of the bed load deposited, that is, <4 cm diameter granules); (3) many excavated lithic pieces exhibit only slight abrasion, as reflected in the observation of arête and edge widths measuring ≤100 μm. Moreover, although it is not possible at present to link all surface finds to the excavated context, the identification of a refit between a core recovered from the dense stratified deposit and one surface flake clearly shows that at least a portion of the surface material derives directly from the *in situ* level (Fig. 4a). More precise interpretation of site preservation is based on observations drawn from the excavation, with the most plausible possibilities limited to either good preservation of the site and most of the assemblage, or a slight redistribution in close proximity of the original activity location (Supplementary Information, part B).

Technology of the Lomekwi 3 stone tools

Based on the lithic material recovered in 2011 and 2012, the current total assemblage ($n = 149$ surface and *in situ* artefacts) incorporates

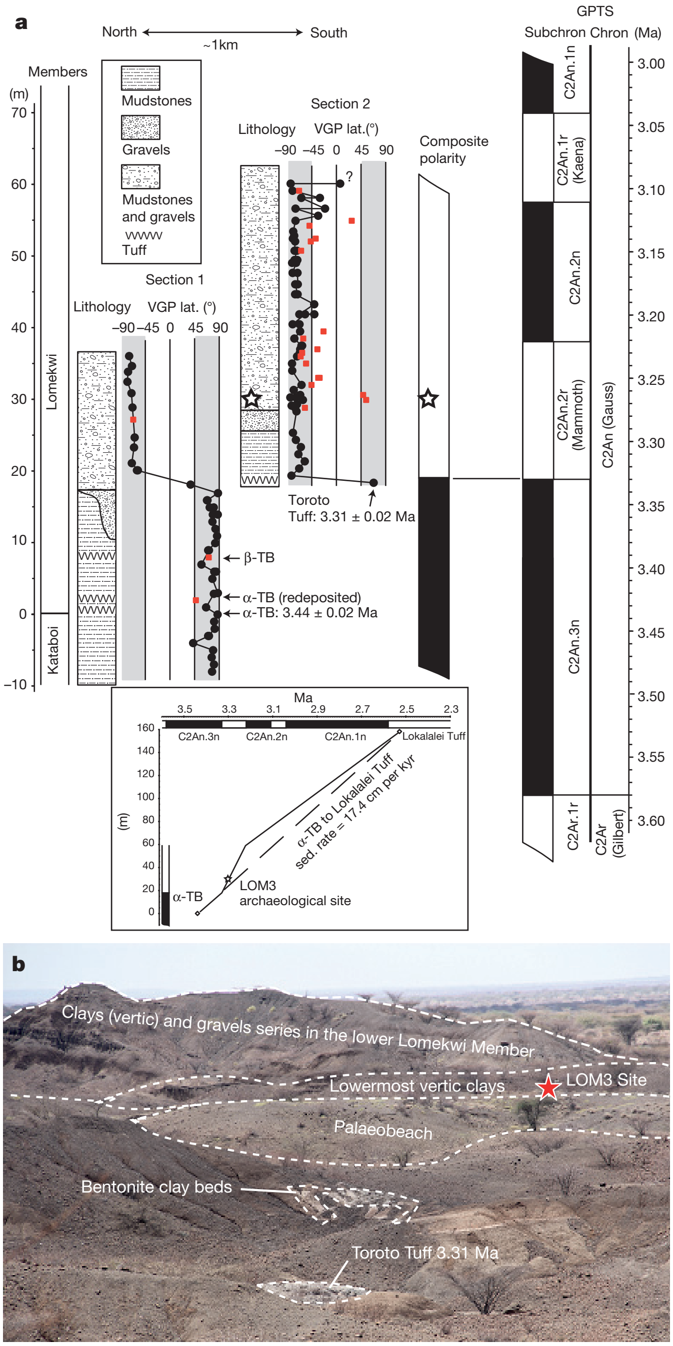

Figure 3 | Chronostratigraphic framework for LOM3.
a, Chronostratigraphic framework for LOM3 (star) with generalized stratigraphic columns and magnetostratigraphic alignment to the geomagnetic polarity time scale (GPTS) in context of dates of tuffaceous markers (± 1 s.d.) and stratigraphic nomenclature for Members of the Nachukui Formation[26,30]. A linearly interpolated date of 3.3 Ma for the *in situ* stone tools is consistent with the site's magnetostratigraphic position within the reverse polarity interval that is correlated to reverse subchron C2An.2r (Mammoth Subchron) dated at 3.33–3.21 Ma[31]. **b**, Photograph facing north showing geographic and stratigraphic relationship between Toroto Tuff, paleobeach, and LOM3.

83 cores, 35 flakes (whole and broken), seven passive elements or potential anvils, seven percussors (whole, broken or potential), three worked cobbles, two split cobbles, and 12 artefacts grouped as indeterminate fragments or pieces lacking diagnostic attributes (Extended Data Table 1a).

Cores are made predominantly from heavy and large-sized cobbles or blocks of lava (mean of the cores: 167 × 147.8 × 108.8 mm, 3.1 kg; Extended Data Table 2). Basalts (34.90%) and phonolites (34.23%) are the dominant raw materials represented, followed by trachy-phonolite (23.49%; Extended Data Table 1b), all of which were available in local paleo-channels. Initial survey of a conglomerate source less than 100 m from the site shows that cobbles and blocks of all sizes were available locally, from which the largest were consistently selected. Most cores were flaked from one striking platform onto one single surface, resulting in several superposed and contiguous unidirectional removals (unifacial partial exploitation), sometimes along a longer part of the perimeter. A few specimens show unifacial partial exploitation by multidirectional removals, while others show bifacial flaking. Significant knapping accidents occurred during flaking, with numerous hinge and step flake terminations visible on cores (Fig. 4a), though more invasive and feather terminating flakes were also often successfully removed. In some cases, cores display a series of shorter (<1 cm) contiguous small scars along a more limited portion of the platform edge, although it is not yet clear whether this results from the knapping techniques employed, or reflects the utilization of some artefacts in heavy-duty tasks.

To reconstruct more accurately the techniques and reduction strategies used to produce the LOM3 artefacts, an experimental program was undertaken to replicate the lithics found at the site from the same raw materials available locally at LOM3. Together with the technological analysis of the archaeological material, these replication experiments suggest that the LOM3 knappers were using techniques including passive hammer[34,35] and/or bipolar[34] (Extended Data Fig. 6) that have to-date rarely been identified in the Oldowan[21,22,36,37]. The average size and weight of the LOM3 cores (Extended Data Table 2) renders direct freehand percussion an arduous undertaking; however, it cannot be ruled out for some of the smaller cores.

The technological features of flakes and flake fragments are clear, unequivocal and seen repeatedly, demonstrating that they were intentionally knapped from the cores. They range from 19 to 205 mm long (Fig. 5d and Extended Data Table 2) and frequently present cortex on their dorsal surfaces, sometimes on their striking platforms, or both. Three pieces in particular bear localized battered areas on their dorsal surfaces—including the specimen that refits onto the *in situ* core (Fig. 4a)—showing that blanks were sometimes used for percussive activities before flake removal and that at least some individual blocks were involved in several distinctively different modes of use.

The largest and heaviest (up to 15 kg) pieces in the assemblage were made on large blocks of basalt or coarse trachy-phonolite. They have flat natural surfaces that could enable their stabilization for use (Fig. 5a, b and Extended Data Fig. 7a). Comparisons with other described anvils from the Early Stone Age and experiments suggest these can be interpreted as anvils or passive elements[38,39]. Three of these show a similar wear and fracture pattern. The largest piece exhibits along one lateral plane a series of divergent step fractures associated with crushing marks and an additional concentration of impact damage on one horizontal surface (Fig. 5a). The other two pieces have non-invasive step fractures along a greater or lesser portion of their high-angled intersecting surfaces (edges) that are associated with crushing and impact marks (Fig. 5b and Extended Data Fig. 7a). A further two cobbles show heavy battering marks concentrated on a convex area and are interpreted as passive elements. Seven medium-sized cobbles display battering marks and/or impact damage associated with fractured surfaces and are interpreted as hand-held percussors or active elements (Extended Data Figs 7b, c).

Discussion

LOM3 core and flake techno-morphology does not conform to any observed pattern resulting from accidental natural rock fracture. On the contrary, LOM3 cores and flakes bear all the techno-morphological characteristics of debitage products. Data reported on accidental flakes from chimpanzee nut-cracking sites[40] falls closer to the flake size spectrum observed at early Oldowan sites than to the size range of LOM3 flakes (Extended Data Table 2). LOM3 knappers were

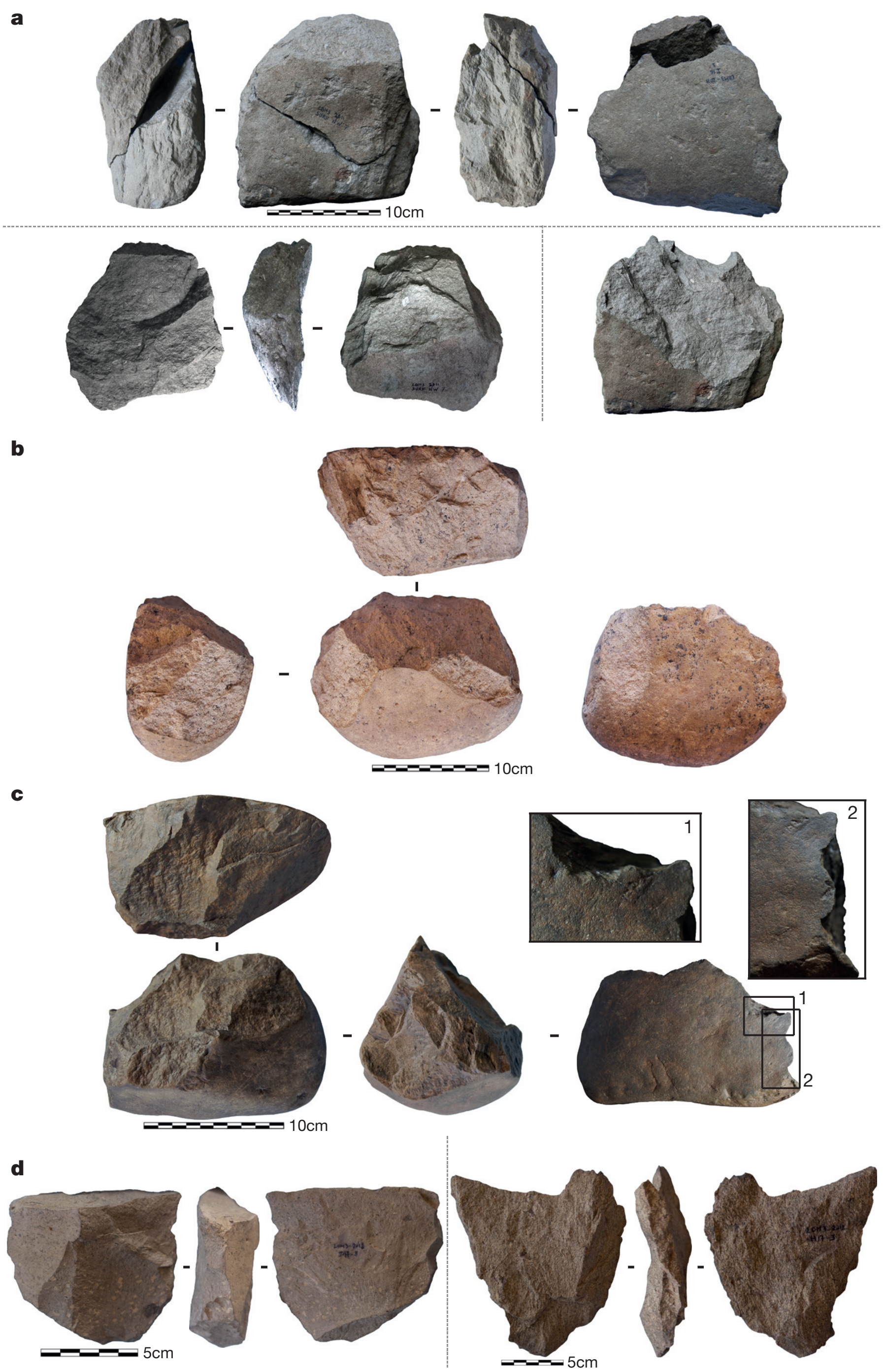

Figure 4 | Photographs of selected LOM3 artefacts. **a**, *In situ* core (LOM3-2011-I16-3, 1.85 kg) and refitting surface flake (LOM3-2011 surf NW7, 650 g). Unifacial core, passive hammer and bipolar technique. Both the core and the flake display a series of dispersed percussion marks on cortex showing that percussive activities occurred before the removal of the flake, potentially indicating the block was used for different purposes. **b**, *In situ* unifacial core (LOM3-2012-H18-1, 3.45 kg), bipolar technique. See Extended Data Fig. 6b for more details. **c**, Unifacial core (LOM3-2012 surf 71, 1.84 kg), passive hammer technique. **d**, Flakes (LOM3-2012-J17-3 and LOM3-2012-H17-3) showing scars of previous removals on the dorsal face. See Supplementary Information part F for 3D scans of lithic artefacts.

able to deliver sufficient intentional force to repeatedly detach series of adjacent and superposed unidirectional flakes, sometimes invasive, and then to continue knapping either by laterally rotating the cores or by flipping them over for bifacial exploitation. However, though multiple flakes were successfully detached, the majority of flake scars terminate as hinge and step fractures. The precision of the percussive motion was also occasionally poorly controlled, as shown by repeated impact marks on core platforms caused by failed blows applied too far from the striking platform edge to induce fracture. LOM3 lithics (cores and flakes) are significantly larger in length, width, and thickness than those from OGS7, EG10 and EG12 at Gona, A.L. 894 at Hadar, and Omo 57 and Omo 123 in Ethiopia; Lokalalei 2C from West Turkana, Kenya; and DK and FLK Zinj from Olduvai Gorge in Tanzania (Extended Data Table 2). Furthermore, the LOM3 anvils and percussors are larger and heavier than those chosen for nut-cracking by wild chimpanzees in Bossou[41] (southeastern Guinea; Extended Data Table 3). The dimensions and the percussive-related features visible on the artefacts suggest the LOM3 hominins were combining core reduction and battering activities and may have used artefacts variously: as anvils, cores to produce flakes, and/or as pounding tools. The use of individual objects for several distinctive tasks reflects a degree of technological diversity both much older than previously acknowledged and different from the generally unipurpose stone tools used by primates[24,25]. The arm and hand motions entailed in the two main modes of knapping suggested for the LOM3 assemblage, passive hammer and bipolar, are arguably more similar to those involved in the hammer-on-anvil technique chimpanzees and other primates use when engaged in nut cracking[42–44] than to the direct freehand percussion evident in Oldowan assemblages. The likely prevalence of these two knapping techniques demonstrates

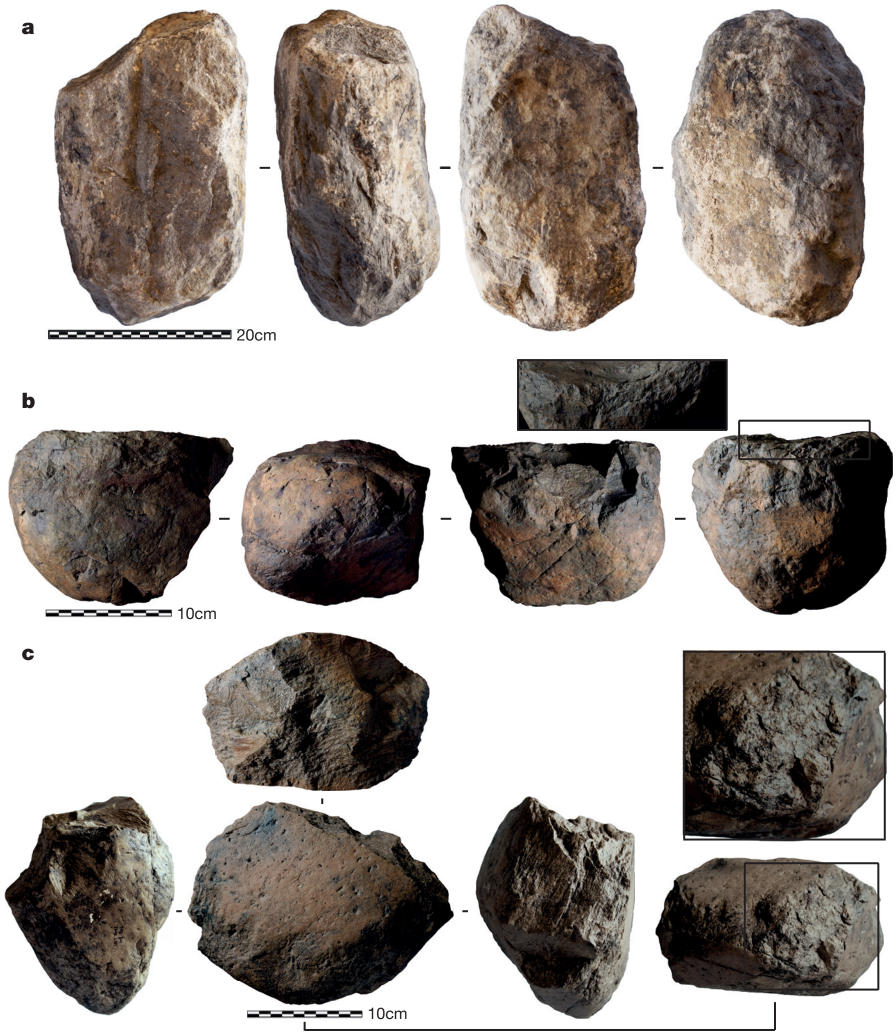

Figure 5 | Photographs of selected LOM3 artefacts. **a**, *In situ* passive element/anvil (LOM3-2012-K18-2, 12 kg). **b**, Passive element/anvil (LOM3-2012 surf 60, 4.9 kg). Both anvils **a** and **b** exhibit similar patterns of macroscopic wear consisting of superposed step fracturing in association with crushing and impacts marks. On **a**, damage is localized on a single lateral face, with battering marks present on one horizontal plane. On **b**, damage is distributed along a greater portion of the perimeter, but in this case no percussive marks are identifiable on the horizontal plane. In both cases, the intensity of the observed wear signature indicates a use in heavy-duty activities. **c**, Unifacial core (LOM3-2012 surf 90, 4.74 kg), bipolar technique and semi-peripheral exploitation. Inset shows crushing marks on the proximal surface of the cobble related to battering activities before or after the knapping of the core. See Supplementary Information part F for three-dimensional scans of lithic artefacts.

the central role that they might have played at the dawn of technology, as previously suggested[21,22,36,37].

LOM3 predates the oldest fossil specimens attributed to *Homo* in West Turkana at 2.34 ± 0.04 Ma[7] by almost a million years; the only hominin species known to have been living in the West Turkana region at the time is *K. platyops*[27], while *Australopithecus afarensis* is found in the Lower Awash Valley at 3.39 Ma in association with cut-marked bones from Dikika[20]. The LOM3 artefacts indicate that their makers' hand motor control must have been substantial and thus that reorganization and/or expansion of several regions of the cerebral cortex (for example, somatosensory, visual, premotor and motor cortex), cerebellum, and of the spinal tract could have occurred before 3.3 Ma. The functional morphology of the upper limb of Pliocene hominins (especially *A. afarensis*, the only species for which contemporaneous fossil hand and wrist elements are known), particularly in terms of adaptations for stone tool making, must be investigated further if this important milestone in human evolution is to be understood more fully (Supplementary Information, part A).

Critical questions relating to how the LOM3 assemblage compares with the previously known earliest hominin stone tool techno-complex, the Oldowan, remain. They are difficult to address because the term Oldowan has been defined differently since it was first employed in 1934 (refs 16, 45–47). The simplest defining characteristics of the Oldowan are that its knappers show the earliest evidence of a basic understanding of the conchoidal fracture mechanics of stone and were able to effectively strike flakes from cores, more often than not knapping using 'grammars of action'[48] and predominantly using the free-hand knapping technique[11,17]. The LOM3 knappers' understanding of stone fracture mechanics and grammars of action is clearly less developed than that reflected in early Oldowan assemblages and neither were they predominantly using free-hand technique. The LOM3 assemblage could represent a technological stage between a hypothetical pounding-oriented stone tool use by an earlier hominin and the flaking-oriented knapping behaviour of later, Oldowan toolmakers. The term 'Pre-Oldowan' has been suggested for modified stones if ever found in deposits older than 2.6 Ma, especially if they are different in terms of knapping skill from the Oldowan *sensu stricto*[49] (this is not to be confused with previous uses of the same term by some authors to describe the early Oldowan period between 2.6–2 Ma[50]). The LOM3 assemblage may therefore concord with such a premise. We assert, however, that the technological and morphological differences between the LOM3 and early Oldowan assemblages are significant enough that amalgamating them would mask important behavioural and cognitive changes occurring among hominins over a nearly 2-million-year timespan. A separate name for the LOM3 assemblage is therefore warranted. Given the paradigmatic shift that LOM3 portends for models that aim to converge environmental change, hominin evolution and technological origins, the name Lomekwian is proposed. In any scenario, the LOM3 stone tools mark a new beginning to the known archaeological record, now shown to be more than 700,000 years older than previously thought.

Note added in proof: The recently described LD 350-1 partial mandible from Ethiopia now provides the earliest evidence of the genus *Homo* at 2.8 Ma (Villmoare, B. *et al.* Early *Homo* at 2.8 Ma from Ledi-Geraru, Afar, Ethiopia. *Science*, 347, 1352–1355). The LOM3 artefacts still predate the known origins of *Homo* by half a million years and the question of what hominin species made them remains.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Supplementary Information is available in the online version of the paper.

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Author Contributions S.H. and J.E.L. directed field research and co-wrote the overall paper. C.S.F., C.J.L., A.L. and X.B. recorded sedimentological and stratigraphic data, conducted geological mapping, and wrote sections of the paper. C.S.F. interpreted tephra data. C.J.L. interpreted paleomagnetic data. S.P., J.-Ph.B., S.L., C.K. and L.L. conducted paleontological survey. S.P., J.-Ph.B. and L.L. analysed and interpreted fossil material. L.L. directed scanning of artefacts. S.P. laser scanned artefacts and excavation surfaces, and wrote sections of the paper. R.L.Q. interpreted isotopic data and wrote sections of the paper. C.S.F., C.J.L., R.L.Q., R.A.M., J.D.W. and D.V.K. analysed geological samples. G.D. developed protocols for tool replication experiments and wrote sections of the paper. S.H., H.R., N.T., M.B., S.C., S.L. and C.K. conducted archaeological survey and excavation. S.H., H.R., A.A., N.T. and M.B. analysed and interpreted lithic material and wrote sections of the paper. M.B. performed lithic replication experiments. S.C. provided spatial data. S.L. discovered the LOM3 site.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to S.H. (sonia.harmand@stonybrook.edu) or J.L. (jason.lewis@stonybrook.edu).

METHODS

Paleomagnetic analyses. All samples from the Lomekwi outcrops were collected from fresh surfaces uncovered by digging into the exposures for at least 20 cm. Before each hand-cut block was extracted, *in situ* azimuths and dips were recorded on a sample using a compass-inclinometer. Samples were taken typically at nominal 1 m vertical stratigraphic intervals, or as the distribution of fine-grained strata allowed. Two sections were sampled, separated from each other by about 1 km north to south across the landscape (Extended Data Fig. 2). Overlapping Sections 1 and 2 (Fig. 3a) are each composed of a coarsening upward succession of mudstones abruptly overlain by gravels and followed by a thick unit of gravels and mudstones, which likely records a lacustrine regression and the emplacement of a prograding alluvial fan. Inset in Fig. 3a shows stratigraphic thickness of composite section plotted against key chronostratigraphic levels (α-Tulu Bor (α-TB), 3.44 $\pm$ 0.02; Toroto Tuff, 3.31 $\pm$ 0.02 Ma; C2An.3n/.2r boundary, 3.33 Ma[31]; Lokalalei Tuff, 2.53 $\pm$ 0.02).

At Section 1 (Fig. 3a), sampling began at about 10 m below the lowermost stratigraphic level of the α-Tulu Bor Tuff. Sampling continued upwardly from the α-Tulu Bor Tuff for another 35 m, for a total of ~45 m sampled. At Section 2 (Fig. 3a), sampling commenced at the Tororo Tuff. Sampling started upwardly from the Toroto Tuff for about 10 m to the level of the archaeological horizon at LOM3, and then proceeded upwardly for another 35 m for a total sampled stratigraphic thickness of about 45 m at Section 2.

For laboratory analyses, samples were cut into standard cube-shape specimens (~10 cc) using a lapidary saw and sandpaper. All magnetic remanence measurements were made with a 2G DCSQUID rock magnetometer in the shielded room at the Paleomagnetics Laboratory of Lamont-Doherty Earth Observatory (Columbia University). The natural remanent magnetization (NRM) of a specimen was subjected to progressive Thermal Demagnetization (TD) using 14 to 17 steps at 100, 50 and 25 °C increments in the temperature range of 100–700 °C. Data from consecutive high-temperature steps were used for principal component analysis (PCA[51]) to fit least-square lines tied to the origin for the final demagnetization trajectories defining the characteristic remanent magnetization (ChRM) as revealed on orthogonal projection plots (Extended Data Fig. 3a). Magnetic susceptibility values were determined with a Bartington MS2B instrument for each specimen initially and after each TD heating step to monitor any laboratory-induced magnetochemical alteration. The virtual geomagnetic pole (VGP) latitude corresponding to the ChRM direction was used to determine the magnetostratigraphic polarity sequence. In Fig. 3a, filled black circles joined by lines (isolated red squares) denote accepted (rejected) data with maximum angular deviation (MAD) values $<15^\circ$ ($>15^\circ$) from principal component analyses. Characteristic remanent magnetizations were isolated after the removal of a pervasive normal polarity overprint unblocked by a TD range of 600–670 °C for the coarse alluvial fan strata (essentially all of Section 2 above the Toroto Tuff) and a TD range of 400–550 °C for the finer strata (for example, mudstones from the lower part of Section 1).

Pedogenic carbonate stable carbon isotopic analysis. Sedimentological field analysis identified eleven paleosols with discernible preserved B_K horizons. Ten paleosols were sampled from Section 2011-1, and one from 2011-2 (Extended Data Fig. 2). Carbonate nodules were extracted from paleosols >30 cm below the contact with overlying stratum with vertic features within peds showing slickensided surfaces. Twenty-four cross-sectioned nodules (five from one paleosol at LOM3, 2011-2) were sampled with a 0.5 mm carbide drill bit (Foredom Series) and loaded into v-vials for single acid baths (multi-prep device). Forty-seven isotopic analyses were conducted on a Micromass Optima mass spectrometer in the Department of Earth and Planetary Sciences at Rutgers University. Samples were reacted at 90 °C in 100% phosphoric acid for 13 min. $\delta^{13}C_{VPDB}$ values are reported in the standard per mil (‰) notation: $= (R_{sample}/R_{standard} - 1)\times 1000$, relative to Vienna-Pee Dee Belemnite through analysis of laboratory standard NBS-19 (Extended Data Fig. 4). Analytical error is $\pm$ 0.05‰. Using methods of ref. 32, we subtracted 14‰ from the $\delta^{13}C_{VPDB}$ values of pedogenic carbonate to convert to the isotopic equivalent of organic carbon ($\delta^{13}C_{om}$) and used the equation: $f_{wc} = \{\sin[-1.06688 - 0.08538(\delta^{13}C_{om})]\}^2$ to generate estimates of fraction woody canopy cover for classification into UNESCO categories of African vegetation. Categories were taken from White[52] and have the following $\delta^{13}C_{VPDB}$ value ranges of pedogenic carbonates[32]: (1) forest: continuous stand of trees at least 10-m tall with interlocking crowns with greater than 80% woody cover ($\delta^{13}C_{VPDB}$: > -11.5 ‰), (2) woodland/bushland/thicket/shrubland: woodland is an open stand of trees at least 8 m tall with woody cover >40% and a field layer dominated by grasses; bushland is an open stand of bushes between 3 m and 8 m tall with woody cover >40%; thicket is a closed stand of bushes and climbers between 3 m and 8 m tall; shrubland is an open or closed stand of shrubs up to 2 m tall ($\delta^{13}C_{VPDB}$: -11.5 to -6.5‰), (3) wooded grassland: land covered with grassland and has 10–40% tree or shrub cover ($\delta^{13}C_{VPDB}$: -6.5 to -2.3 ‰) and (4) grassland: land covered with herbaceous plants with less than 10% tree and shrub cover ($\delta^{13}C_{VPDB}$: < -2.3 ‰). We also calculated percent C_4 biomass using a simple linear mixing model assuming -12‰ and -26‰ as the C_4 and C_3 end members, respectively[53].

Site scanning. To document the uncovering of the *in situ* artefacts and fossils during the excavation, we took frequent 3D scans of the surface of individual squares with the OptiNum RE handheld device (manufactured by Noomeo Products, France) with a maximum spatial resolution of 300 μm. Additionally, thanks to a collaboration between Zoller & Fröhlich GmbH and Autodesk, we had access to a recently developed high-resolution industrial 3D scanner operated by M. Reinköster. This scanner was able to scan the entire site, registering 500,000 3D points each second, with a spatial resolution of <3,000 μm, and recording for several minutes continuously. After the laser scan a 3D photo was taken which can be draped around the scan. The site was scanned in this manner after each day of excavation. In this way, a high-resolution 3D digital model can be created for the entire site, and individual squares, showing the evolution of the excavation and the original context and gradual uncovering of the *in situ* artefacts and fossils.

Stone tool scanning. A representative sample of the LOM3 artefacts were scanned at the National Museums of Kenya and the Turkana Basin Institute facility in Turkwel, using a LMI Technologies R3 Advance portable structured light scanner (LMI Technologies, Vancouver, Canada), calibrated to the size of the objects in question, with the calibration grids being accurate to 50 μm. For colour texture overlay, a Canon 600D/Rebel T3i SLR digital camera was also calibrated with the scanner and images from this formed the base of the colour texture. The textured files are saved in .obj format and non textured files (for 3D printing or similar purposes) are saved in .stl format. These scans and 3-D digital models are available at (http://africanfossils.org/search).

Sample size. No statistical methods were used to predetermine sample size

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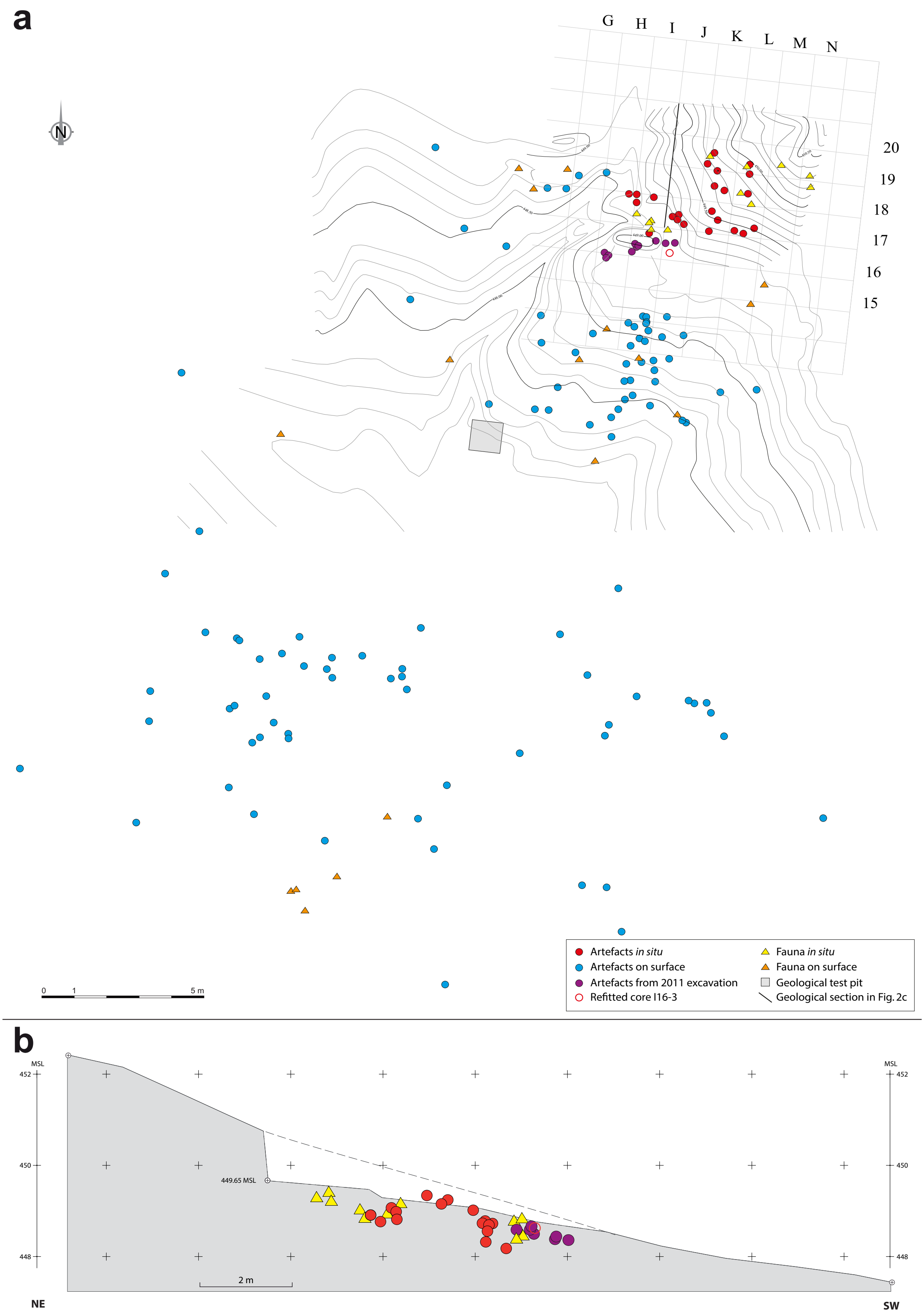
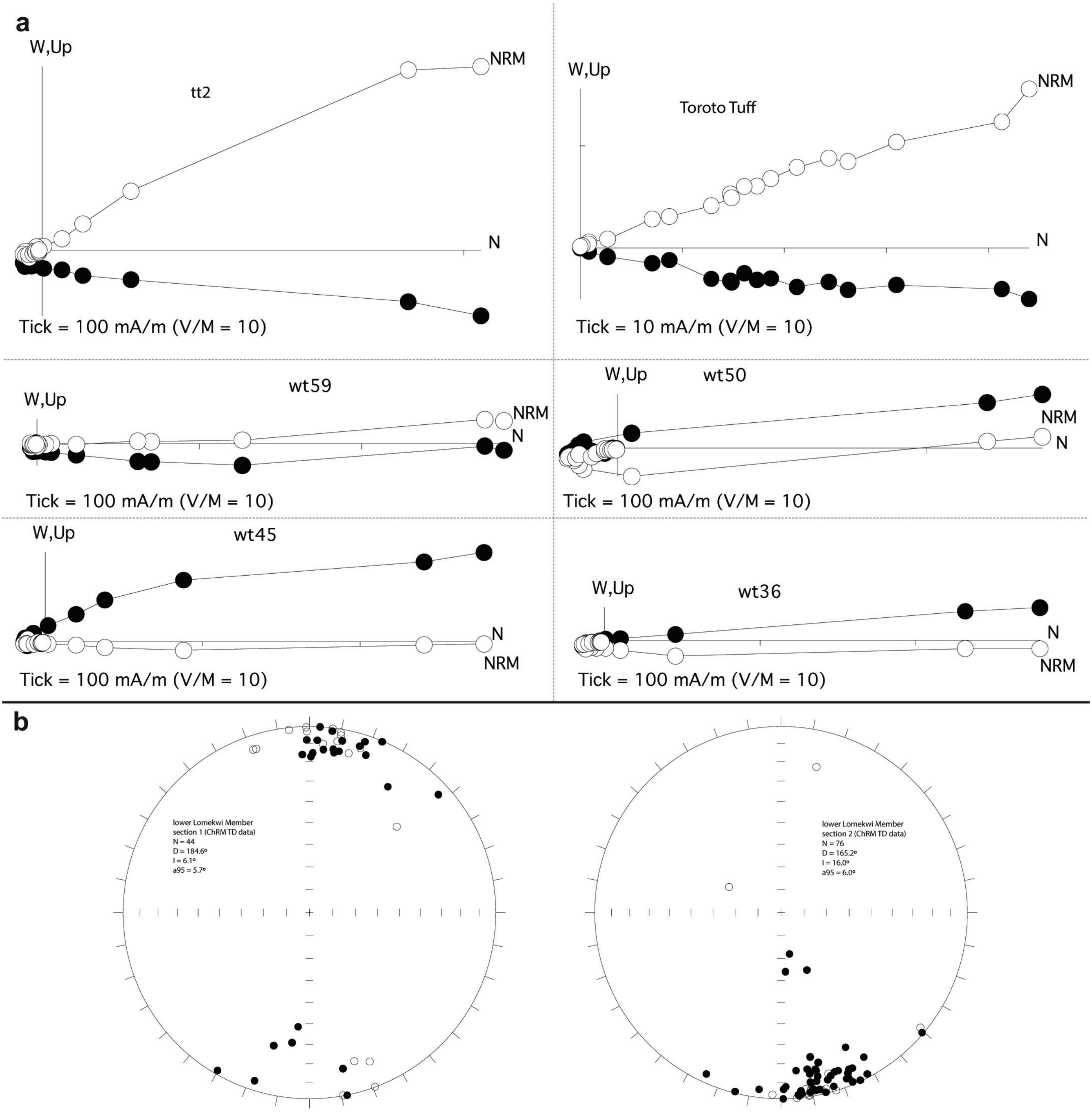


Extended Data Figure 1 | Map and schematic section at LOM3. **a**, Map showing *xy* coordinates of artefacts and fossils recovered *in situ* and from the surface at the site in 2011 and 2012. **b**, Schematic section showing vertical distribution of *in situ* artefacts and those located in the slope deposit at the excavation. Key is the same for both figures.

b

	N Lat (d mm.mmm)	E Long (dd mm.mmm)
base 2011-1	3 52.441	35 45.201
top 2011-1	3 52.219	35 45.325
base 2011-2	3 51.806	35 45.183
top 2011-2	3 51.814	35 45.292
base 2012-2	3 51.627	35 45.228
top 2012-2	3 51.662	35 45.251
base 2012-6	3 51.875	35 44.932
top 2012-6	3 51.969	35 44.971
base 2012-8	3 51.679	35 45.268
top 2012-8	3 51.699	35 45.282
base 2012-9	3 51.473	35 45.205
top 2012-9	3 51.512	35 45.181
base 2013-1	3 51.485	35 44.973
top 2013-1	3 51.511	35.45.003

Extended Data Figure 2 | Geology of the LOM3 site. **a**, Stratigraphic sections around LOM3 (locations in **b**), showing relationship of site to marker tuffs and lithofacies. Sections aligned relative to top of flat-pebble conglomerate unit. **b**, GPS coordinates of stratigraphic sections (WGS84 datum).

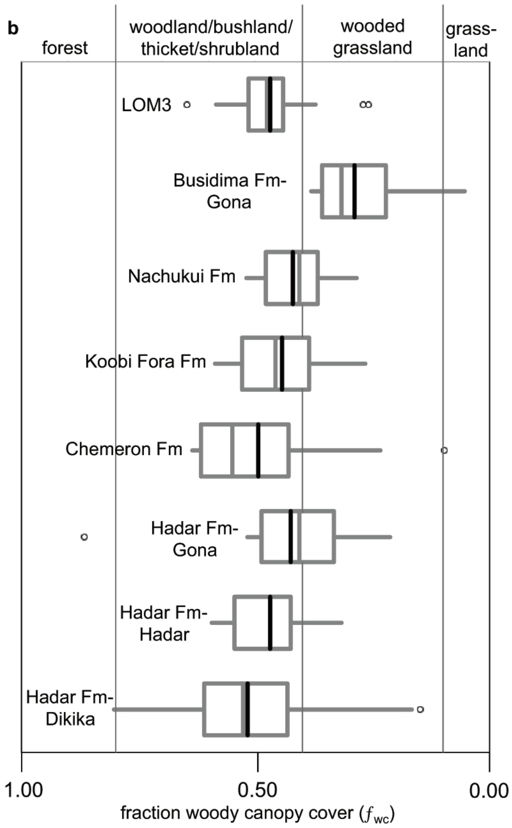


Extended Data Figure 3 | Paleomagnetic data. **a**, Representative vector end-point plots of natural remanent magnetism thermal demagnetization data from specimen Toroto Tuff, tt2, wt59, wt50, wt45, wt36. Open and closed symbols represent the vertical and horizontal projections, respectively, in bedding coordinates. TD treatment steps: NRM, 100°, 150°, 200°, 250°, 300°, 350°, 400°, 450°, 475°, 500°, 525°, 550°, 575°, 600°, 625°, 650°, 660°, 670°, 675°, 680°, 690°, and 700°. V/M = 10 denotes a ~10 cc cubic specimen. **b**, Equal-area projections for Section 1 (left) and Section 2 (right) of the lower Lomekwi Member (see Fig. 3a). Open and closed symbols are projected onto the upper and lower hemisphere, respectively, in bedding coordinates. Plotted are ChRM sample-mean directions for accepted samples only (that is, those with MAD values <15°). Overall mean directions were calculated after inverting the northerly (normal) directions to common southerly (reverse) polarity.

a

Sample No.	$\delta^{13}C_{VPDB}$ (‰) ± 1σ	No. of analyses	f_{wc} (%)	C_4 biomass (%)
LOM-PC 4A*	-7.4 ± 1.6	2	48	33
LOM-PC 4B*	-8.2 ± 0.1	2	54	27
LOM-PC 4C*	-9.4 ± 0.2	2	65	18
LOM-PC 6A	-8.2 ± 0.5	2	55	27
LOM-PC 8A	-6.2 ± 0.2	2	37	41
LOM-PC 10A	-7.2 ± 0.2	2	46	34
LOM-PC 11/12A	-7.9 ± 0.2	2	52	29
LOM-PC 11/12B	-7.6 ± 0.3	2	49	32
LOM-PC 12A	-7.7 ± 0.0	2	50	30
LOM-PC 12/13A	-6.2 ± 0.5	2	37	42
LOM-PC 14A	-7.4 ± 0.2	2	48	33
LOM-PC 16A	-6.7 ± 0.4	2	42	38
LOM-PC 18A	-7.1 ± 0.0	2	45	35
LOM-PC 21A	-6.9 ± 0.3	2	43	36
LOM-PC 27A	-4.7 ± 0.6	2	26	52
LOM-PC 28A	-7.7 ± 0.3	2	50	31
LOM-PC 29A	-7.8 ± 0.2	2	51	30
LOM-PC 32A	-4.9 ± 0.2	2	27	51
LOM-PC 33A	-8.4	1	56	26
LOM-PC 37A	-7.2 ± 0.2	2	46	34
LOM-PC 39A	-7.1 ± 1.1	2	45	35
LOM-PC 44A*	-7.7 ± 0.1	2	50	30
LOM-PC 44B*	-6.8 ± 0.1	2	42	37
LOM-PC 45A	-8.7 ± 0.1	2	58	24

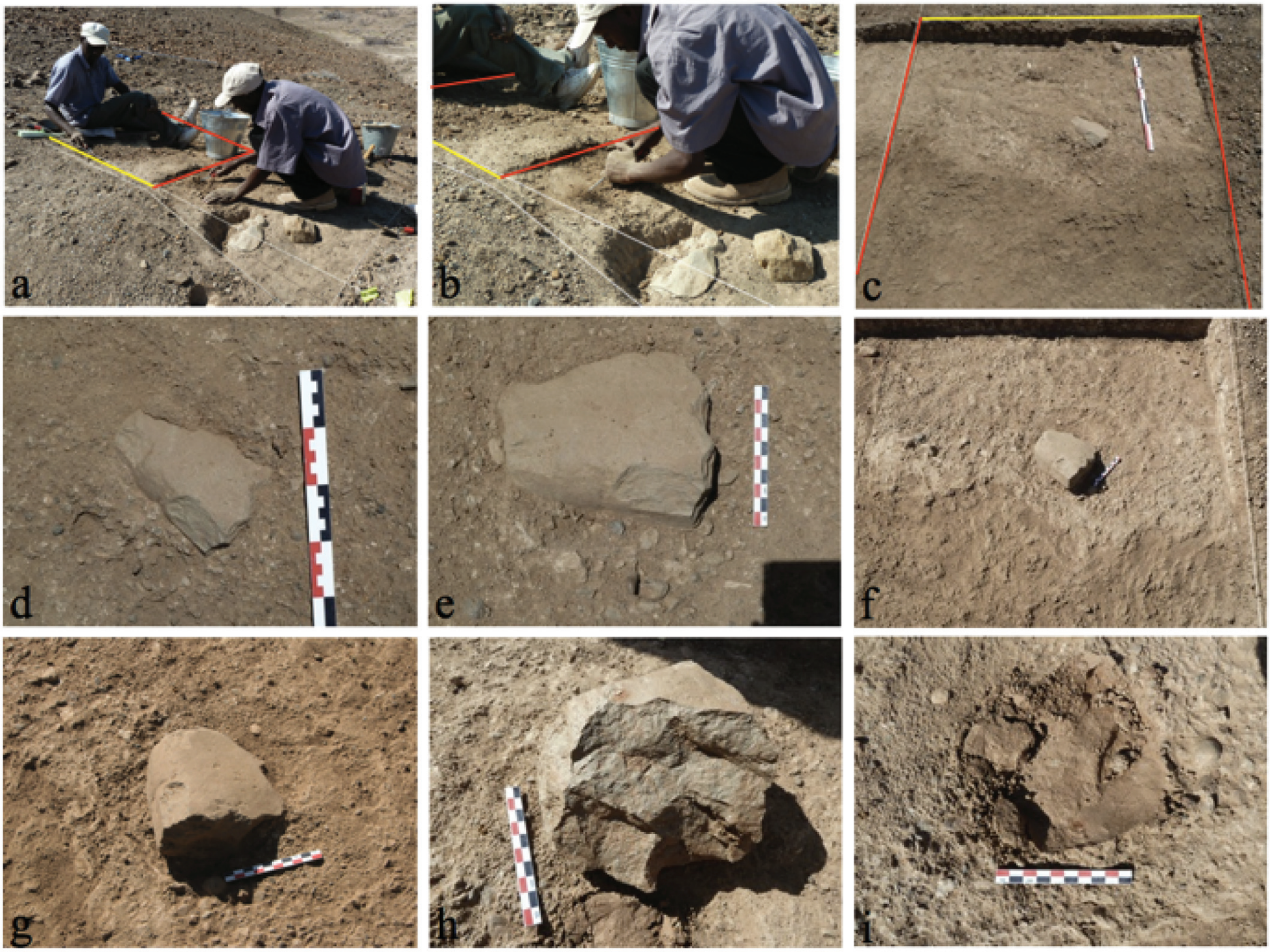
b



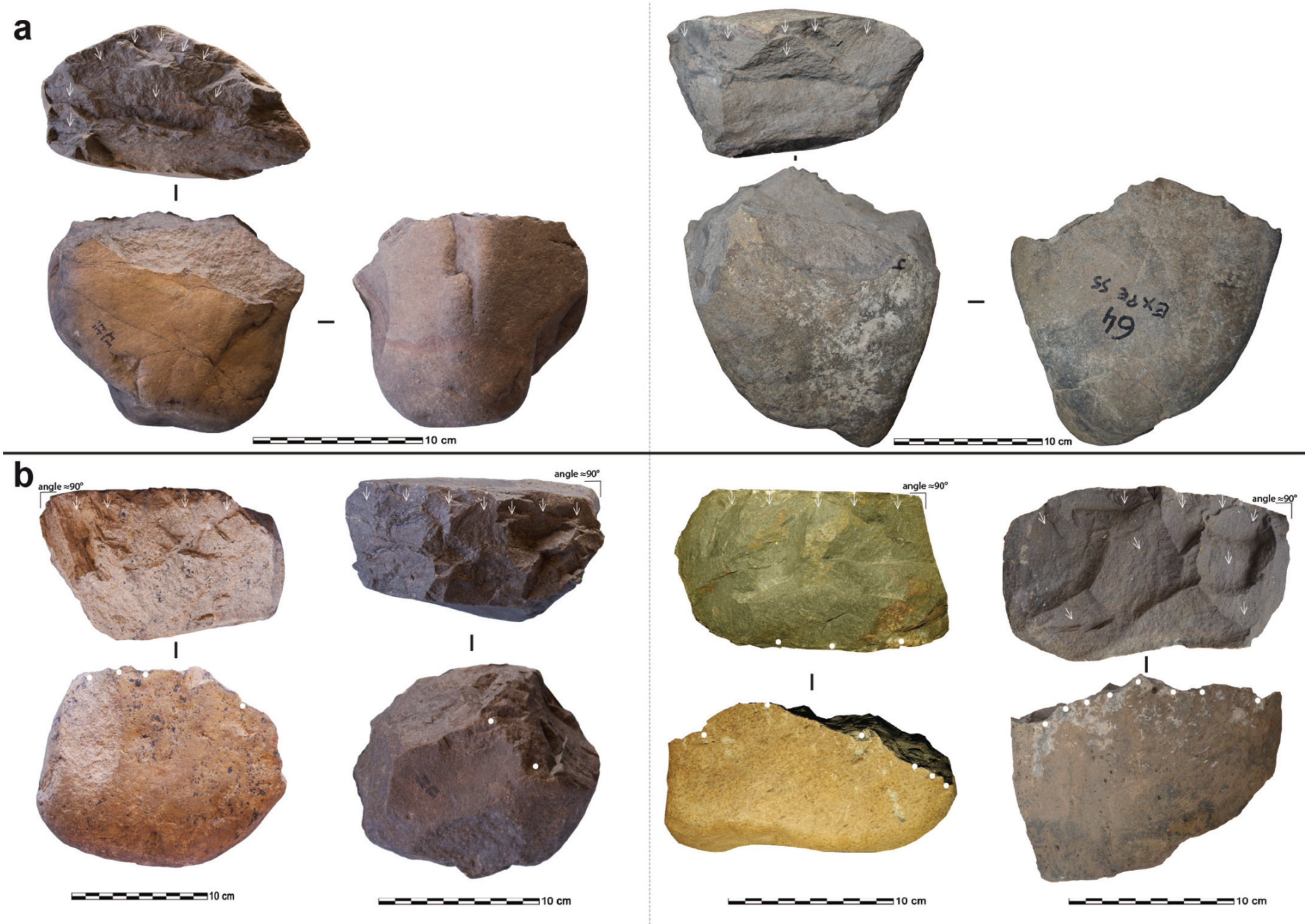
c

	LOM3 (3.3 Ma)	Busidima Fm-Gona (2.7-2.5 Ma)	Nachukui Fm (3.2-3.4 Ma)	Koobi Fora Fm (3.2-3.4 Ma)	Chemeron Fm-Tugen Hills (3.2-3.4 Ma)	Hadar Fm-Gona (3.2-3.4 Ma)	Hadar Fm-Hadar (3.2-3.4 Ma)	Hadar Fm-Dikika (3.2-3.4 Ma)
nodules, analyses	23, 47	28, 31	17, 95	34, 35	12, 14	15, 15	19, 19	141, 183
$\delta^{13}C$ mean ±1σ	-7.3±1.1‰	-5.0±1.3‰	-6.7±0.9‰	-7.0±1.2‰	-7.6±2.6‰	-6.8±1.9‰	-7.3±1.1‰	-7.9±1.7‰
$\delta^{13}C$ range	-9.4 to -4.7‰	-6.4 to -1.2‰	-8.0 to -5.1‰	-8.8 to -4.8‰	-11.4 to -2.2‰	-12.5 to -4.1‰	-9.3 to -5.5‰	-11.5 to -3.1‰
f_{wc} mean ±1σ	47±9%	29±9%	42±7%	44±10%	50±20%	43±15%	47±10%	52±14%
f_{wc} range	26-65%	5-39%	28-52%	27-60%	10-79%	21-87%	32-63%	15-80%

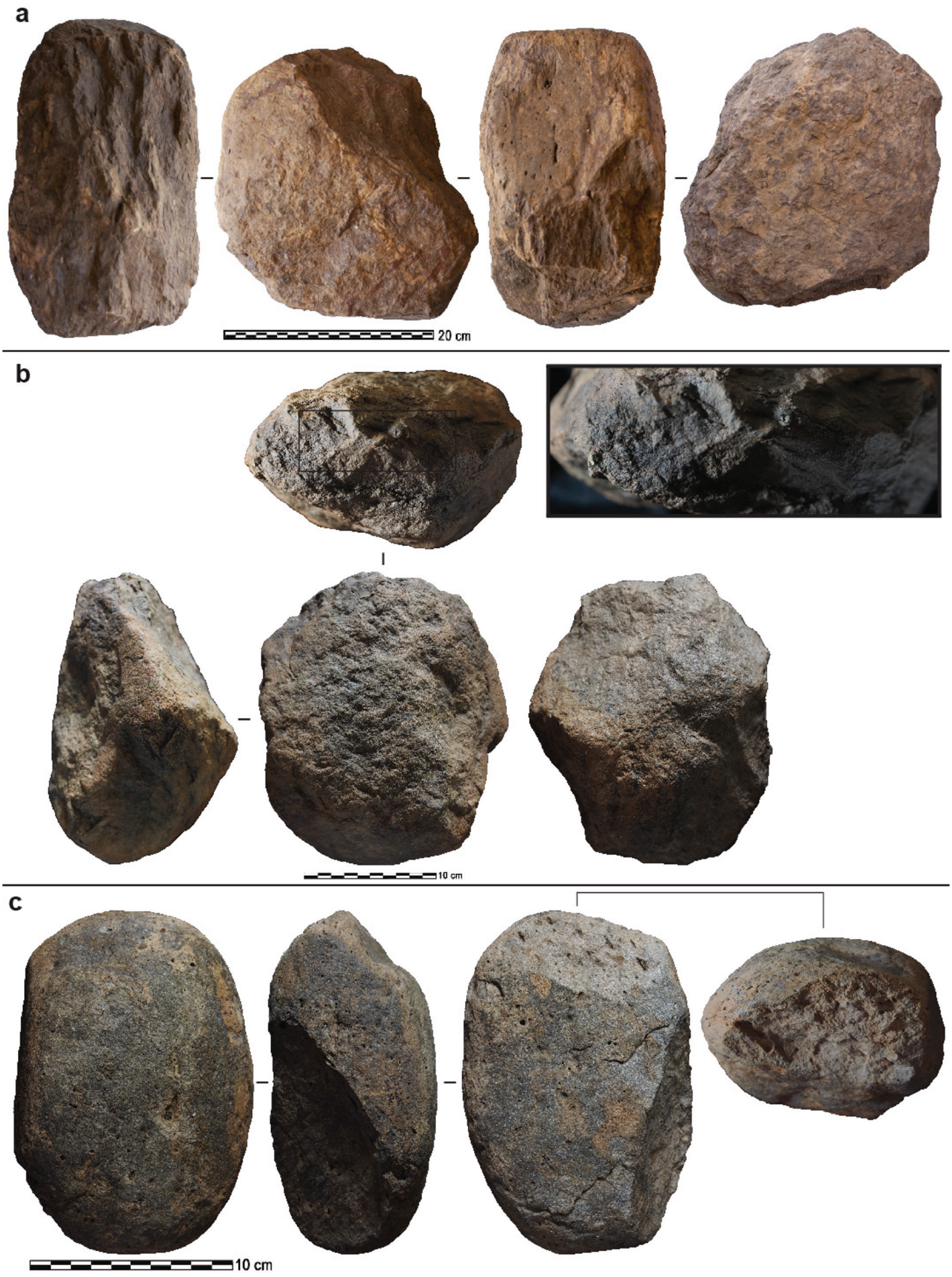
Extended Data Figure 4 | Paleoenvironmental reconstruction through pedogenic carbonate stable carbon isotopic analysis. **a**, LOM3 paleosol $\delta^{13}C_{VPDB}$ values (‰) ± 1σ, number of analyses, fraction woody canopy cover (f_{wc}) and percent C_4 biomass contribution to soil CO_2. Asterisk denotes nodules sampled at the LOM3 site, 2011-2b (see Extended Data Fig. 2a). **b**, Schematic box and whisker plots of f_{wc} from the LOM3 (3.3 Ma, this study) and Gona[33,54,55] (Busidima Fm, 2.5–2.7 Ma) lithic sites and other East African hominin localities from 3.2–3.4 Ma[54–61] relative to UNESCO structural categories of African vegetation[32,52]. Grey box denotes 25th and 75th percentiles (interquartile range); whiskers represent observations within upper and lower fences (1.5 × interquartile range); black line shows mean value; grey line equals median value; black circles indicate mild outliers. **c**, Summary statistics of paleosol $\delta^{13}C_{VPDB}$ values and f_{wc} from LOM3 (3.3 Ma) and Gona[33,54,55] (2.5–2.7 Ma) lithic sites and other East African hominin localities from 3.2–3.4 Ma[54–61]. LOM3 $\delta^{13}C_{VPDB}$ values are significantly lower than those from the Busidima Formation at Gona (*t*-test, $P < 0.001$) and have a mean value that indicate 18% more woody canopy cover. When compared to paleosol $\delta^{13}C_{VPDB}$ values of the Koobi Fora, Nachukui, Chemeron, and Hadar formations from 3.2 to 3.4 Ma, LOM3 $\delta^{13}C_{VPDB}$ values are not significantly different (one-way ANOVA, $P > 0.05$).



Extended Data Figure 5 | Gradual uncovering of core I16-3 from *in situ* pliocene sediment. **a**, Photograph showing square I16 at the beginning of excavation. Yellow line indicates north wall of square (July 16, 2011, 12.14 p.m.). **b**, Close-up of square I16 indicating complete burial of as-yet-uncovered artefact I16-3 (12.14 p.m.). **c**, Square I16 after excavation had begun and artefact I16-3 was initially exposed (2:11 p.m.). **d**, Close-up of artefact I16-3 after being initially exposed (2.12 p.m.). **e**, Close-up of artefact I16-3 after further excavation (3.02 p.m.). **f**, Square I16 after further excavation (5.32 p.m.). **g**, Close-up of artefact I16-3 after further excavation (5.34 p.m.). **h**, Close-up of artefact I16-3 after being completely freed from the surrounding matrix and flipped over for inspection (5.36 p.m.). **i**, Close-up of impression from under artefact I16-3 (5.47 p.m.).



Extended Data Figure 6 | Photos of selected LOM3 artefacts compared with similar experimental cores. Together with the technological analysis of the archaeological material, our replication experiments suggest that the LOM3 knappers were using passive hammer technique, in which the core, usually held in both hands, is struck against a stationary object that serves as the percussor[34] (also referred to as on-anvil, block on block or *sur percuteur dormant*[35]) and/or bipolar technique, in which the core is placed on an anvil and struck with a hammerstone[34]. **a**, Unifacial passive hammer cores. Left is archaeological piece LOM3-2012 surf 106 (2.04 kg); right is experimental piece Expe 55 (3.40 kg) produced using the passive hammer technique. Selection of relatively flat blocks with natural obtuse angles. The flake removal process starts from a slighly prominent part of the block (white arrows show the direction of removals). The removals tend to be invasive. The flaked surface forms a semi-abrupt angle with the platform surface. A slight rotation of the block ensures its semi-peripheral exploitation. **b**, Unifacial bipolar cores. Left are archaeological pieces LOM3-2012-H18-1 (left, 3.45 kg) and LOM3-2012 surf 64 (right, 2.58 kg); right are experimental pieces Expe 39 (left, 4.20 kg) and Expe 24 (right, 2.23 kg) produced using the bipolar technique. The block selected are thicker and more quadrangular in shape with natural angles ≈90°. Flakes are removed from a single secant platform (white arrows show the direction of removals). The flaked surface forms an abrupt angle with the other faces of the block. Impacts due to the contrecoups (white dots) are visible on the opposite edge from the platform.



Extended Data Figure 7 | Photographs of selected LOM3 artefacts. **a**, Passive element/anvil (LOM3-2012 surf 50,15 kg). Heavy sub-rectangular block displaying flat faces and therefore a natural morphology and weight which would enable stability. **b**, Hammerstone showing isolated impact points (LOM3-2012 surf 33, 3.09 kg) and **c**, Hammerstone showing isolated impact points (LOM3-2012 surf 54, 1.63 kg), associated with a flake-like fracture on one end.

Extended Data Table 1 | Numerical data on the LOM3 lithic assemblage (2011, 2012).

a

ARTEFACTS		*in situ*	slope deposit	surface	total
core	passive hammer technique	1	1	33	35
	bipolar technique	2	3	26	31
	passive hammer and/or freehand technique	0	0	6	6
	bipolar and/or passive hammer technique	2	0	4	6
	of indeterminate technique	1	0	4	5
flake, whole or broken		10	3	22	35
percussor, whole, broken or potential		0	0	7	7
passive element/potential anvil		2	1	4	7
worked cobble		0	0	3	3
split cobble		0	0	2	2
fragment indet.		1	2	4	7
indet.		0	0	5	5
total		19	10	120	149

b

RAW MATERIAL	N	%
phonolite	51	34.23
trachy-phonolite	35	23.49
basalt	52	34,90
trachyte	2	1.34
vesicular basalt/conglomerate	3	2.01
indet.	6	4.03
total	149	100.00

a, Initial categorisation of the lithic components. **b**, Breakdown of lithic raw materials in the LOM3 assemblage.

Extended Data Table 2 | Comparison of whole flake and core dimensions between LOM3, early Oldowan sites and chimpanzee stone tool sites

				Length				Width				Thickness					
Site	Age (Ma)	Ref.	N	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max	Geo. Mean	Mean Mass
								FLAKES									
LOM3	3.3		26	120	48.8	19	205	110.1	40.7	19	185	43.9	23.4	6	90	59.9	842.4 (N=26)
OGS7	2.6	62	73	39.1*	14.3	13	80	37.1*	14.1	13	74	12.7*	5.07	3	26	14.10	18.9 (N=76)[‡]
EG10	2.6	62	114	37.38*	15.34	14	78	34.63*	13.74	14	78	13.18*	6.26	3	33	13.74	24.9 (N=72)[‡]
EG12	2.6	62	62	34.5*	12.84	15	66	35.55*	13.23	19	66	12.13*	5.76	4	30	13.23	21.5 (N=61)[‡]
AL894	2.36	63[†]	1048	35.9*	23.63	6	134	25.07*	17.57	2	106	7.98*	6.4	1	45	17.1	
LA2C	2.34	16	500	38*	15	12	96	35*	14	7	128	11*	5	3	28	14.00	
Omo57	2.34	14[†]	44	24.75*	10.546	10	58	20.36*	6.851	10	44	7.73*	4.008	1	18	6.85	
Omo123	2.34	14[†]	110	20.8*	7.495	7	50	17.79*	6.485	6	38	5.9*	2.792	1	16	6.49	
DK	> 1.84	64	115	40.18*	14.803	18	111	37.41*	11.215	17	71	11.89*	5.404	4	29	11.22	
FLKZinj	1.76-1.84	64	125	36.78*	12.13	16	82	32.88*	11.59	4	76	11.51*	5.45	4	36	11.59	
Noulo[§]	.0043	40	5	35*	20.62	15	70	48*	27.06	15	90	11.6*	3.21	8	15	20.15	
								CORES									
LOM3	3.3		83	167	23.4	132	260	147.8	23.1	90	210	108.8	21.8	61	170	139	3096.4 (N=81)
OGS7	2.6	62	7	44.14*	13.68	28	67	59*	8.54	45	70	37*	8.2	22	49	45.85	78[‡]
EG10	2.6	62	16	83.33*	10.34	69	105	60.9*	9.18	44	80	45.27*	12.36	30	69	61.25	232[‡]
EG12	2.6	62	7	74.45*	8.72	58	93	59.73*	8.06	49	77	43.73*	77.4	25	53	57.94	194 (N=9)[‡]
AL894	2.36	63[†]	38	75.01*	30.32	19.31	136.3	55.33*	22.54	12.21	94.9	35.87*	18.1	7.92	78.2	53.00	
LA2C	2.34	16	70	66*	18	39	123	52*	14	32	95	32*	12	12	78	47.9	
Omo 57	2.34	14[†]	7	37.4*	8.81	25	52	28.8*	7.313	22	40	16.5*	4.721	11	24	26.10	
Omo 123	2.34	14[†]	11	30.5*	12.193	17	56	22.27*	8.186	13	42	13.5*	4.569	9	24	20.93	
DK	> 1.84	64	69	67.93*	19.146	30	117	62.78*	17.992	25	100	48.25*	14.435	18	81	59.04	
FLK Zinj (lava only)	1.76-1.84	64	49	76.35*	12.57	53	95	78.85*	16.26	49	112	59*	12.3	37	87	70.82	

Dimensions are in mm, Mass in g. *Denotes significant difference with LOM3 (*t*-test, one-tailed, $P < 0.0001$). Given the small sample sizes and potential non-normal nature of stone tool measurements, a non-parametric test such as Mann–Whitney would be preferable, but this would require access to the raw measurement data from the other Oldowan sites, access to which is currently beyond the scope of this work. The Student's *t*-test is very robust, however, as deviations from normality do not affect it very much, and it is currently the only option when working with published data summaries.

†The summary data from this publication was not in the correct format for direct comparison with LOM3, so information for this table was provided directly by the author in the form of personal communication.

‡Data from ref. 17, hence differing sample sized from ref. 62.

§Dimensions of accidentally produced flakes from chimpanzee nut-cracking activity are included here for comparative purposes, although a direct technological comparison would be inappropriate as those pieces are not the result of intentional flake manufacture and do not bear the classic technological flake characteristics like those from LOM3 and early Oldowan sites.

Extended Data Table 3 | Comparison of anvils and percussors dimensions found at LOM3 site with anvils and percussors used by non-human primates in Bossou (wild chimpanzees, *Pan troglodytes verus* from ref. 41)

		Length		Width		Thickness		Mass	
Site	N	Mean	Std	Mean	Std	Mean	Std	Mean	Std
ANVILS									
LOM3	7	19.40	±6.26	15.44	±3.69	12.54	±3.17	6511.29	±4901.64
BOSSOU	32	16.10	±6.47	11.1*	±4.38	7.30*	±2.97	2200.00*†	±2210.00
PERCUSSORS									
LOM3	7	13.38	±3.67	10.75	±2.81	7.84	±2.33	1602.00	±1120.55
BOSSOU	35	12.00	±2.65	7.70*	±1.86	5.20*	±1.08	700.00*	±330.00

Dimensions are in cm, Mass in g. *Denotes significant difference with LOM3 (*t*-test, two-tailed, $P < 0.0199$). Given the small sample sizes and potential non-normal nature of stone tool measurements, a non-parametric test such as Mann–Whitney would be preferable but this would require access to the raw measurement data from ref. 41, access to which is currently beyond the scope of this work. The Student's *t*-test is very robust, however, as deviations from normality do not affect it very much and it is currently the only option when working with published data summaries.
† $N = 31$.