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LETTERS

Evidence for stone-tool-assisted consumption of animal tissues before 3.39 million years ago at Dikika, Ethiopia

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The oldest direct evidence of stone tool manufacture comes from Gona (Ethiopia) and dates to between 2.6 and 2.5 million years (Myr) ago[1]. At the nearby Bouri site several cut-marked bones also show stone tool use approximately 2.5 Myr ago[2]. Here we report stone-tool-inflicted marks on bones found during recent survey work in Dikika, Ethiopia, a research area close to Gona and Bouri. On the basis of low-power microscopic and environmental scanning electron microscope observations, these bones show unambiguous stone-tool cut marks for flesh removal and percussion marks for marrow access. The bones derive from the Sidi Hakoma Member of the Hadar Formation. Established ^{40}Ar–^{39}Ar dates on the tuffs that bracket this member constrain the finds to between 3.42 and 3.24 Myr ago, and stratigraphic scaling between these units and other geological evidence indicate that they are older than 3.39 Myr ago. Our discovery extends by approximately 800,000 years the antiquity of stone tools and of stone-tool-assisted consumption of ungulates by hominins; furthermore, this behaviour can now be attributed to *Australopithecus afarensis*.

The Dikika Research Project area is located in the Lower Awash Valley (Ethiopia) and is bordered on the north by Gona and Hadar and on the south by the Middle Awash research areas (Fig. 1). Work there (led by Z.A.) began in 1999 and has focused on survey in Hadar (>3.8 to 2.9 Myr ago) and Busidima Formation (2.7 to <0.6 Myr ago) deposits, both of which are exposed in their entirety within the project area[3,4]. This work has resulted in the discovery of a diverse and well preserved fauna, the discovery of several hominin fossils including a nearly complete juvenile *Australopithecus afarensis* (DIK-1-1) and a complete definition of the hominin-bearing Hadar Formation[3–6].

In January 2009, the Dikika Research Project systematically collected fossils from localities just opposite the DIK-1 locality in the Andedo drainage, which predominantly exposes the Sidi Hakoma (SH) Member of the Hadar Formation (3.42–3.24 Myr ago; Fig. 1). Archaeological survey was conducted simultaneously in these same localities. In the course of this work, four fossils were identified with surface modifications which, based on field observations, resembled stone-tool cut marks[7]. These fossils were subsequently studied with optical and environmental scanning electron microscopy (ESEM) (see Methods and Supplementary Information). Secondary electron imaging (SEI) and energy dispersive X-ray (EDX) spectrometry data show that the marks on two of these fossils (DIK-55-2 and DIK-55-3) formed before fossilization. Optical and ESEM observations show that the marks lack the morphology indicative of trampling and biochemical marks, and that these two specimens have modifications clearly indicative of stone tool use, including cutting and percussion.

Both bones were found on the surface at the same locality: DIK-55. Stratigraphically this locality, an area of approximately 25 m × 50 m, can be placed into the section described previously for the nearby DIK-1 locality. It is below a low ridge that exposes only the lowermost sediments of the SH Member and below the level of a limestone marker (SH-lm) with a stratigraphically scaled age of 3.39 Myr ago, providing a minimum age for the site (Fig. 1 and Supplementary Information). Nowhere in the entire Andedo drainage are sediments above the lacustrine Triple Tuff 4 (TT-4) marker (3.24 Myr ago) exposed, providing a minimum age for the entire section. Specimen DIK-55-2 was found on the slope below the SH-lm marker and DIK-55-3 was found on the flats just in front of this slope. Fossils from this locality lack adhering matrix, indicating that they derive from a ~1.5-m-thick sand bed that outcrops here. This sand is unique compared to many of the fossil-bearing sands of the SH Member (such as at DIK-1) in that it is not strongly cemented and thus its fossils lack adhering matrix.

DIK-55-2 (Fig. 2 and Supplementary Information) is a right rib fragment of a large ungulate, probably size 4 (cow-sized) or larger. Marks A1 and A2 are perpendicular to the cortical surface, V-shaped in cross-section with internal microstriations and diagnosed as high-confidence stone-tool cut marks. Mark B is a more obliquely oriented mark that shaves off the bone surface within which are microstriations, all consistent with a high-confidence stone-tool-inflicted mark from cutting, scraping and/or percussion. An indentation (mark C) with microstriations and crushing of the bone surface is a high-confidence hammerstone percussion mark described in Supplementary Information.

DIK-55-3 (Fig. 3 and Supplementary Information) is a femur shaft fragment of a size 2 (goat-sized) young bovid. The surface is densely marked (Fig. 3a). Mark A is perpendicular to the cortical surface and has clear microstriations running out one end (Fig. 3b, c), diagnosed as a high-confidence cut mark. Mark D (Fig. 3d–f) is a dense cluster. One prominent mark within D (Fig. 3d) has crushing of the bone surface with microstriations and is diagnosed as a high-confidence percussion mark. Mark E (Fig. 3g, h) is obliquely oriented, shaves off surface bone, has microstriations and a shouldered edge highly consistent with a stone-tool cut mark. Marks H1 and H2 overlap. H1 has clear microstriations, is associated with the broken edge of the bone and swirls in a way typical of a percussion mark. H2 shaves off bone

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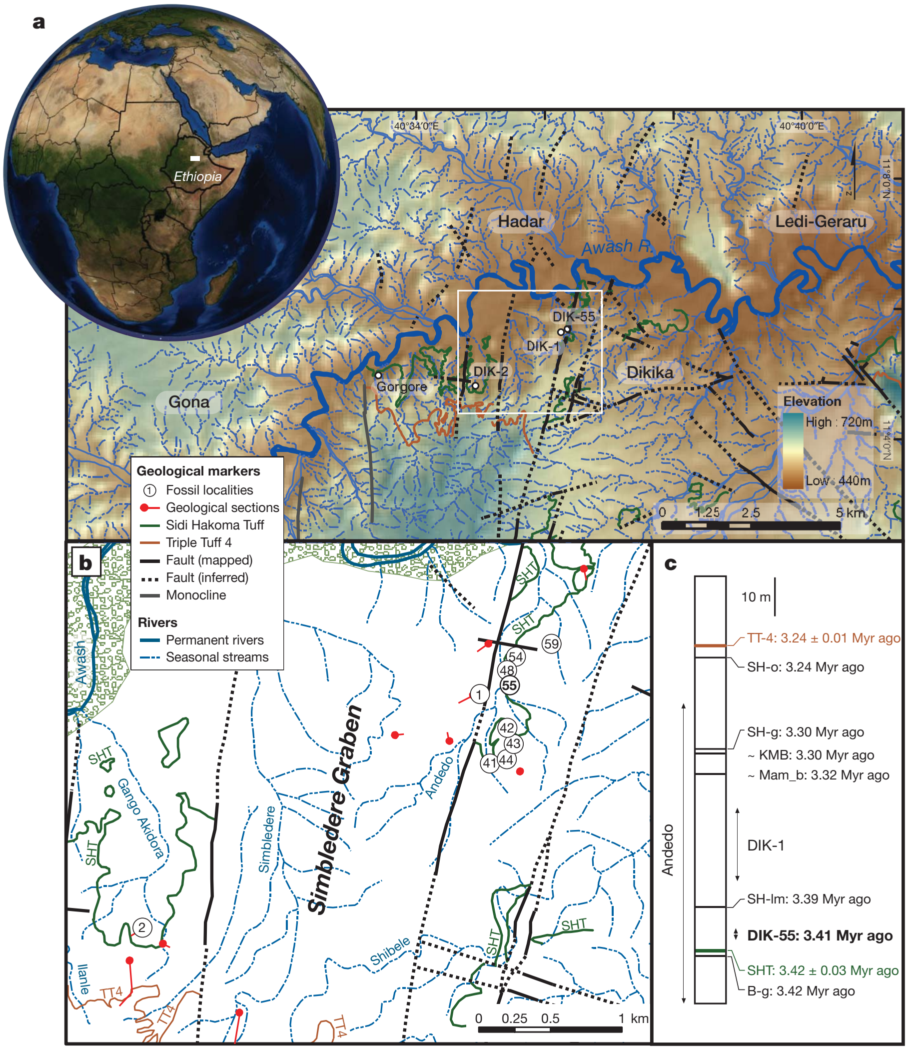

Figure 1 | Geographic and stratigraphic location of DIK-55. a, Map of a portion of the Dikika Research Project area showing DIK-55 (modified bone locality), DIK-1 and DIK-2 (hominin localities), and relevant faults and sections. **b**, Detailed map showing the position of the DIK-55 and surrounding palaeontological localities. **c**, A composite stratigraphic column of the Andedo drainage and surrounding Simbledere region showing the position of the modified bones at DIK-55. Stratigraphic scaling of marker units (SH-o, SH-g, SH-lm and B-g) are based on ^{40}Ar–^{39}Ar ages of the Sidi Hakoma Tuff (SHT) and TT-4 recalibrated to reflect an updated age of the Fish Canyon Sanidine standard[28]. Stratigraphic scaling between these two radiometrically dated tuffs provides a sedimentation rate of 427.8 m Myr^{-1}, which is applied to the ages of the Basal gastropodite (B-g), Sidi Hakoma limestone (SH-lm), DIK-1 excavation, Sidi Hakoma gastropodite (SH-g) and Sidi Hakoma ostracodite (SH-o). These stratigraphically scaled ages are consistent with a correlation to the position of the Kada Damoumou Basalt ~3.3 Myr ago and the lowermost boundary of the Mammoth palaeomagnetic subchron within the Gauss chron (Mam_b.; chron 2An.2r at 3.319 Myr ago[29]; both are recorded elsewhere in the Hadar Formation[28,30]).

surface and has clear microstriations, consistent with stone-tool cut marks and a scraping motion. DIK-55-3 has other high-confidence stone-tool-inflicted marks, and there is at least one mark (mark I) of uncertain agency (Supplementary Information). This specimen does not have any notches of the type that are sometimes associated with hammerstone percussion on long bones[8–10], but this may be owing to post-depositional breakage of the edges that removed such notches.

The cut marks demonstrate hominin use of sharp-edged stone to remove flesh from the femur and rib. The location and density of the marks on the femur indicate that flesh was rather widely spread on the surface, although it is possible that there could have been isolated patches of flesh. The percussion marks on the femur demonstrate hominin use of a blunt stone to strike the bone, probably to gain access to the marrow. The external surfaces of ribs have thin sheaths of flesh, so the scraping marks on the fossil rib suggest stripping off of these sheaths.

The presence of stone-tool-modified bones and by implication the use of stone tools at Dikika by 3.39 Myr ago greatly increases the known antiquity of this behaviour. The earliest demonstration of stone tool production known thus far is after 2.6 Myr ago at several localities in Ethiopia and Kenya[1,11–14]. It is not possible to demonstrate from the modified bones whether the stone tools were knapped for this purpose or whether naturally occurring sharp-edged stones were collected and used. No stone artefacts or sharp-edged stones were found in association with the bones at DIK-55. However, stone tool production and consequently archaeological accumulations are not expected at this locality given the sedimentary environment characterized by the palaeo-Awash River emptying into a nearby lake[3,4]. In this relatively low-energy depositional environment, clasts suitable for stone tool production are not present (few particles larger than fine gravel, 8 mm diameter). Within the exposed SH Member, the distance from DIK-55 to cobble-sized raw materials (>64 mm) is ~6 km (at Gorgore; Fig. 1). Thus, in this instance the absence of evidence for stone tool production in the immediate vicinity of the cut-marked bones may reflect landscape-level raw material constraints.

The bones presented here are the earliest evidence for meat and marrow consumption in the hominin lineage, pre-dating the known evidence by over 800 kyr[2]. Pending new discoveries, the only hominin species present in the Lower Awash Valley at 3.39 Myr ago to which we can associate this tool use is *A. afarensis*[5,15]. Whether *A. afarensis*

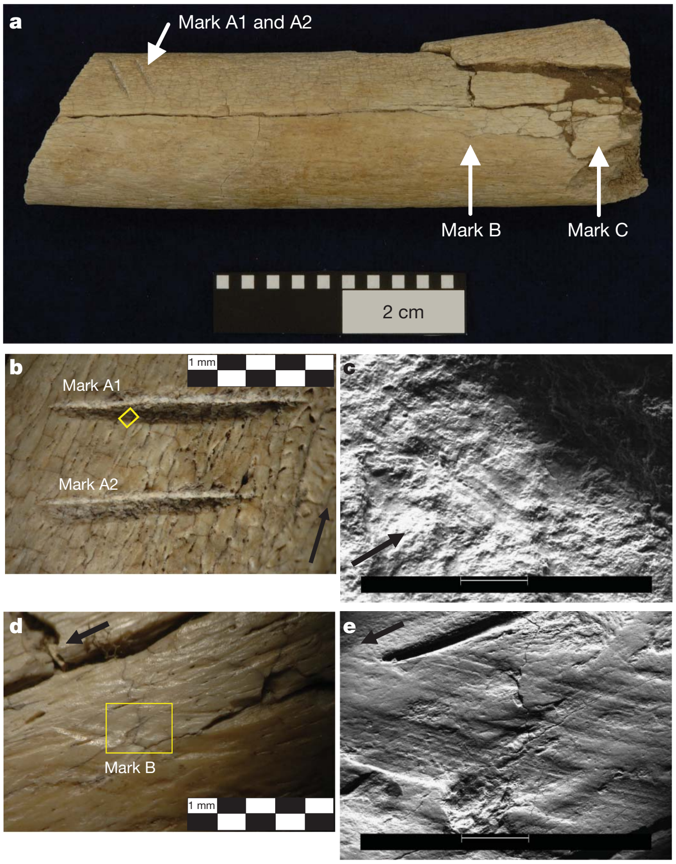

Figure 2 | Stone-tool-inflicted marks on DIK55-2, a rib of a probably size 4 or larger ungulate. **a**, The exterior surface of DIK-55-2, and the location of each of the surface marks. The rib is oriented such that the rib head (broken off) would be to the left. Dashed rule, 4 cm. **b**, Marks A1 and A2 (high-confidence stone-tool cut marks) under low-power optical magnification; the yellow rectangle demarcates **c**. Scale bar, 5 mm. **c**, ESEM image showing microstriations indicative of cutting with a stone tool. Scale bar, 100 µm. **d**, Mark B (high-confidence stone-tool-inflicted mark) under low-power optical magnification, indicative of a cutting and scraping action or percussion; the yellow rectangle demarcates **e**. Scale bar, 5 mm. **e**, ESEM image showing microstriations indicative of stone tool action. Scale bar, 500 µm. **b**–**e**, The direction of the rib head is indicated by the black arrows. See Supplementary Information for the details of mark C.

also produced stone tools remains to be demonstrated, but the DIK-55 finds may fit with the view that stone tool production predates the earliest known archaeological sites and was initially of low intensity (one-to-a-few flakes removed per nodule) and distributed in extremely low density scatters across the landscape such that its archaeological visibility is quite low[16]. The evidence presented here offers a first insight into an early phase of stone tool use in hominin evolution that will improve our understanding of how this type of behaviour originated and developed into later, well recognized, stone tool production technologies.

METHODS SUMMARY

Bone surfaces were examined under ×8–80 magnifications with adjustable incident light from a bifurcated light source. ESEM was used to further document marks and to collect SEI/EDX data (see below) but was not needed for diagnosis and identification. Here (and in Supplementary Information) the nested terminology of Gifford-Gonzalez[17] is used to draw inferential distinctions between the actors responsible for producing the marks, the effectors used to make the marks and causal action. A mark is considered high confidence in its diagnosis to effector if it has all the criteria defined in the literature for that mark. A distinction is made in mark diagnoses between general (stone tool, tooth, or unidentifiable) and specific (cut mark versus percussion mark), with the caveat that specific identifications are more tenuous given the overlap between percussive and cutting damage indicated by these specimens.

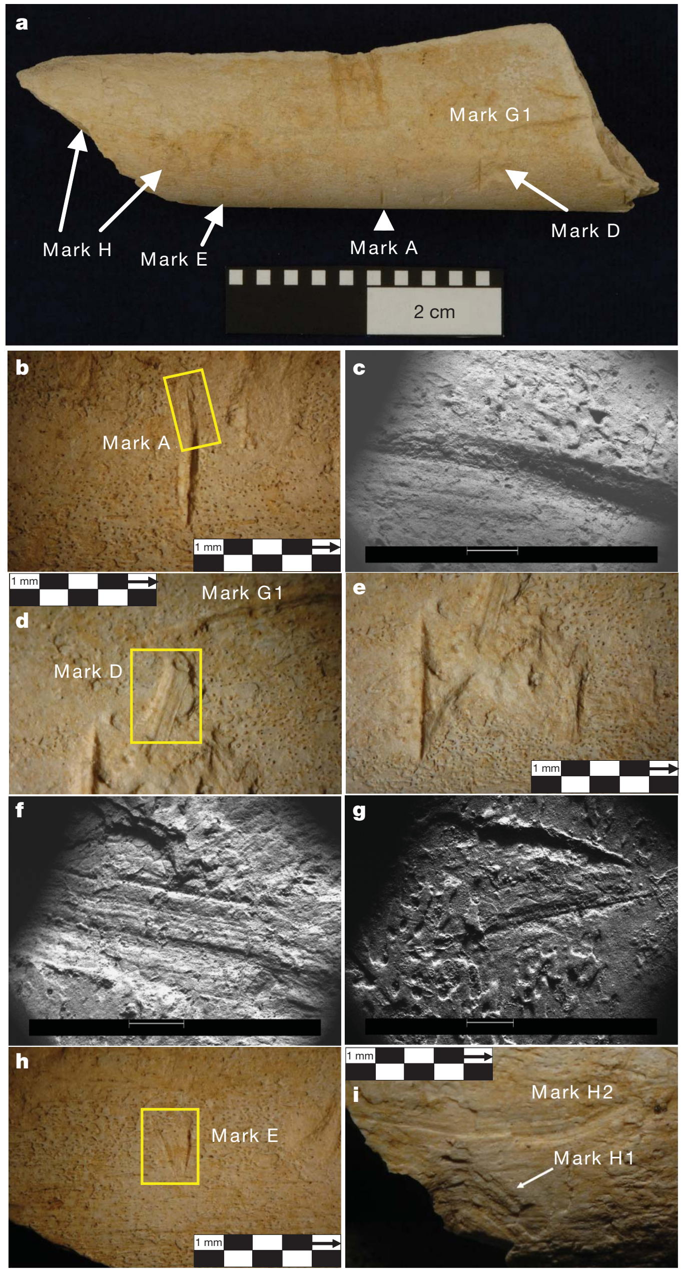

Figure 3 | Stone-tool-inflicted marks on DIK-55-3, a femur shaft of a size 2 young bovid. **a**, The exterior surface of DIK-55-3. The bone is oriented such that the proximal end is to the right. Dashed rule, 4 cm. The location of each of the surface marks is shown in close-up in **b**–**i**. **b**, Mark A (high-confidence stone-tool-inflicted mark) under low-power optical magnification shows clear microstriations indicative of cutting with a stone tool; the yellow rectangle shows the position of **c**. **c**, ESEM image further documenting microstriations. **d**, Mark G1 leading into the large area of clustered damage designated mark D; D shows both stone-tool percussion damage (shown in yellow rectangle that demarcates **f**) and recurrent cutting by a stone tool. **e**, Continuation of mark D showing high-confidence stone-tool-inflicted marks. **f**, ESEM image showing microstriations indicative of stone tool action. **g**, ESEM image of the area indicated by the rectangle in **h** of mark E showing microstriations indicative of stone tool action. **c**, **f**, **g**, Scale bars, 100 µm. **h**, Mark E (high-confidence stone-tool-inflicted mark) under low-power optical magnification possibly produced by a slicing motion from the distal end. **i**, Marks H1 and H2 under low-power magnification, both high-confidence stone-tool-inflicted marks; H1 is probably a percussion mark and H2 is probably a cut mark. **b**–**i**, The direction of the femur head is indicated by the black arrows on the scale, which is 5 mm. See Supplementary Information for marks B, C, F and I, not shown here.

Modern collection damage was assessed visually and chemically. The patina inside the surface marks resembles the surface patina and not the lighter colour of the interior fossil bone made visible by some modern damage on the ends. The elemental composition, measured with EDX spectrometry, of the marks and adjacent surfaces indicates that fossilization occurred after mark formation (Supplementary Information). EDX spectrometry was also applied to a rock fragment, probably of igneous origin, embedded in one mark (Supplementary Information). The marks were assessed for criteria described as indicative of biochemical damage[18,19] and of trampling[20,21] and found to lack key criteria (Supplementary Information). Finally, we used well known and described morphological criteria[9,18,19,22–27] to distinguish between cut marks, percussion marks and tooth marks. Further comparisons were made to experimentally generated stone cut-marked, percussion-marked and carnivore-tooth-marked comparative specimens. Identifications were blind tested for correspondence between three experienced taphonomists and zooarchaeologists who examined the specimens under the same light-microscope conditions. The results showed a high correspondence and agreement that most marks were stone-tool inflicted (Supplementary Information).

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions S.P.M. is the project archaeologist. Z.A. is the head of the project and palaeoanthropologist. C.W.M. described and analysed the fossil bone specimens and surface modifications. J.G.W. is the project geologist. Fauna were analysed by Z.A., D.R. (micromammals and GIS), D.G. (biostratigraphy), R.B. (palaeoenvironments). H.A.B. conducted the ESEM/SEI/EDX study. All authors contributed to the writing of this paper.

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