Pitted stones in the Acheulean from Olduvai Gorge Beds III and IV (Tanzania): A use-wear and 3D approach

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Abstract

The archaeological sequence of Olduvai Gorge Beds III and IV is essential for the study of the evolution of the African Acheulean between ~1.3 and 0.6 Ma. However, no further re-examinations of the lithic assemblages have been published after Mary Leakey's original work. In this paper, we present an analysis of part of these collections, with an emphasis on the microscopic and spatial analysis of percussive marks in the so-called pitted stones. To investigate the function of pitted stones and understand the formation process of depressions on lava cobbles, archaeological pitted stones were compared to

experimental tools used in bipolar knapping, nut-cracking, and flake-splitting activities. Our results demonstrate that features of pitted stones remained homogeneous across Beds III and IV assemblages, with depressions preferentially located on the central areas of the tools and similar use-wear traces inside such depressions. Comparisons with the experimental collection demonstrate that these depressions are rapidly formed when splitting flakes, resulting in elongated morphologies similar to those documented in the archaeological tools. Our results are discussed within the context of other archaeological and nonhuman primate assemblages to further explore the function of pounding activities in which pitted stones could have potentially been involved.

1. Introduction

1.1. Pitted stones: background and definition

Pitted stones—also referred to in the literature as ‘pierres à cupules’ (Chavaillon, 1979), ‘cupstones’ and ‘nut stones’ (Read, 1892; Rowe, 1995; Adams, 2002)—are a type of pounding tool occasionally reported in the archaeological record, and characterized by the presence of distinct depressions on their surfaces. Pitted stones have been found in association with Oldowan (Chavaillon, 2004; Roche et al., 2018; Arroyo and de la Torre, 2018) and Acheulean (Leakey and Roe, 1994; Goren-Inbar et al., 2002) assemblages, as well as in Middle/Upper Paleolithic and late prehistoric periods (e.g., de Beaune, 1989, 1993; Yamamoto, 1990; Kuhn et al., 2009; Holst, 2010; Roda et al., 2012), and their functionality has been a subject of discussion since the 19th century (e.g., Read, 1892; Deishler, 1939). Pitted stones have also been documented as part of modern hunter-gatherers’ tool-kits (e.g., Boshier, 1965; Maguire, 1965; Akerman, 1975; Pardoe et al., 2019), and the primatological record has shown that pounding activities by chimpanzees (Pan troglodytes), macaques (Macaca fascicularis), and capuchin monkeys (Sapajus

libidinosus) also leave similar depressions in hammerstones and anvils (Struhsaker and Hunkeler, 1971; Kortlandt, 1986; Benito-Calvo et al., 2015; Luncz et al., 2016; Gumert et al., 2009; Visalberghi et al., 2007; Haslam et al., 2016).

At Olduvai, Mary Leakey defined pitted stones as cobbles “bearing pecked depressions which are either oblong or circular, occurring singly or in pairs” (Leakey and Roe, 1994, p. 7), suggesting that the larger pieces were used as stationary anvils and the smaller objects as hammerstones. So far, the earliest presence of pitted stones has been documented at FLK North Level 1 in Upper Bed I, FLK North Sandy Conglomerate in Lower Bed II (Leakey, 1971; but see de la Torre and Mora, 2005), as well as at HWK EE in the Lemuta Member (Lower to Middle Bed II) and the Acheulean site of EF-HR in lowermost Upper Bed II (Arroyo and de la Torre, 2018). In these cases, the proportion of pitted stones is consistently lower than any other percussive tools. Jones (1994) noted that pitted stones appear mostly in Beds III and IV, particularly at WK Upper Channel (upper Bed IV), which yields the largest collection of these artifacts (Leakey and Roe, 1994).

To date, no research has been published on the function of the pitted stones from Beds III and IV apart from that of Jones (1994). Although he did not adopt a microscopic approach, Jones (1994) carried out a comprehensive experimental study, concluding that pitted stones were used in bipolar knapping. Jones (1994) also hypothesized that, in combination with *outils écaillés* and punches, pitted stones may have been used to cut rawhide or meat by pounding flakes, and therefore the three types of artifacts were part of the same chaîne opératoire.

Other archaeological and experimental assemblages have linked pitted stones to a variety of activities such as nut-cracking (Goren-Inbar et al., 2002, 2014), bipolar flaking (Leakey and Roe, 1994; Donnart et al., 2009), shellfish pounding (Akerman, 1975; Strudwick, 1995), pigment processing (Britt, 1973), and their function as sockets for bow-

drills or fire-makers (Britt, 1973; Rowe, 1995). The growing literature on the topic suggests that different activities may create depressions on tools classified as pitted stones, making the identification of tasks involved in their use by Olduvai hominins even more challenging. In the current study, we aim to shed light on the function of Olduvai pitted stones from Beds III and IV by applying for the first time a multianalytical approach. Our study includes technotypological and functional analysis, macroscopic GIS techniques, and additional morphological attributes using 3D modeling to create a detailed overview of their characteristics and use-wear traces. In addition, to better assess the function of pitted stones and activities in which they may have been involved, archaeological results are compared to experimental materials, and discussed in the context of other Early Stone Age archaeological assemblages where pitted stones have been identified.

1.2. Olduvai Beds III and IV: stratigraphy and chronology

Beds III and IV are formed by three main lithofacies: fluvial-lacustrine, western fluvial, and eastern fluvial deposits (Hay, 1976). Bed III is best recognised in the stratigraphic sequence of the eastern part of the gorge, where it is characterised by reddish deposits of volcanic detritus consisting of high percentages of claystone as well as sandstone and conglomerate with a thickness ranging between 4.5 and 11 m. Bed IV is a grayish deposit mainly composed of claystone and small percentages of sandstone, siltstone, conglomerate, and tuff, with a variable thickness between 2.4 and 7.3 m (Hay, 1963, 1994).

Olduvai Beds III and IV were explored initially during the early 1930s (Leakey et al., 1931; Leakey, 1954), although the main excavations took place between 1968 and 1971 (Leakey and Roe, 1994). Juma's Korongo (JK) is the only site excavated by Leakey

and associates in Bed III (Kleindienst, 1964, 1973; Leakey and Roe, 1994), while excavations in Bed IV were carried out at three locations: Peter Davies Korongo (PDK), Heberer's Gully (HEB) and Wayland's Korongo (WK; Fig. 1). Except for PDK IV, all sites were in river channel contexts, and were attributed to the Developed Oldowan C or the Acheulean (Leakey and Roe, 1994).

Initial work based on paleomagnetism established that Bed III was formed during the Matuyama chron (>0.7 Ma) and identified the contact between Bed III and IV coinciding with the Matuyama-Brunhes boundary (Brock et al., 1972). Hay (1994), however, argued that this boundary lies within Bed IV, above Tuff IVB. Hay (1994) estimated an age between 1.15 Ma and 0.8 Ma for Bed III, and between 0.8 and 0.6 Ma for Bed IV, while Cerling and Hay (1986) proposed the transition between Beds III and IV at 0.83 Ma, and an age between 1.2 and 0.83 Ma for Bed III. Manega (1993) used $^{40}\text{Ar}/^{39}\text{Ar}$ to date Tuff IIIA at 1.33 Ma, while Tamrat et al. (1995) considered Bed IV older than 0.78 Ma based on palaeomagnetism. In sum, and despite dating uncertainties, there is some consensus in attributing to Beds III and IV an age of between 1.3–1.2 and 0.6 Ma (Manega 1993; Hay, 1994).

During this interval, various episodes of faulting caused a change in the drainage of the Olduvai basin, which shifted from an alluvial-lacustrine to a fluvial-lacustrine depositional regime (Hay, 1994). Cerling and Hay (1986) reported drier and warmer conditions dominated by an alluvial plain and expansion of grasslands, where faunal changes were also observed (Gentry and Gentry, 1978).

2. Materials and methods

2.1. Archaeological pitted stones

Our study focuses on the Beds III and IV assemblages originally studied by Mary Leakey (Leakey and Roe, 1994) and currently housed in the ‘Laetoli Lab’ at Olduvai Gorge. We reviewed the entire lithic collection from JK and identified a total of nine pitted stones. To evaluate possible changes over time on the morphology and use-wear marks, additional pitted stones were selected from HEB ($n = 3$; two from HEB East and one from HEB West) and WK Main Channel ($n = 17$; Fig. 2), resulting in 29 artifacts in total, which cover the stratigraphic sequence from Bed III to upper Bed IV.

2.2. Experimental reference collection

To examine the formation of depressions on Olduvai lava cobbles, we conducted additional experiments to complement our previous reference collection on quartzite battering artifacts (de la Torre et al., 2013). New experiments involved six pounding tools (three active elements and three passive elements) that were used in three different activities (Table 1): one set of tools (Exp #30; Fig. 3A) was used to knap a core using the bipolar technique (sensu Crabtree, 1972); a second set (Fig. 3B) was used to process 2.2 kg of nuts ($n = 318$, *Macadamia integrifolia*, Exp #31); and the third set (Fig. 3C) was used to split flakes (Exp #32), following previous experiments by Jones (1994). All percussive objects were made of lava cobbles, while cores were quartzite blocks. All raw materials were sourced from Olduvai Gorge.

Prior to starting the experiments, all samples were analyzed macro- and microscopically to allow for comparisons of artifact modification and to prevent misidentification of use-wear traces. Experiments took place at the Institute of Archaeology (University College London) by two separate participants and ran for a cumulative time of 126 minutes. Each experimental session was filmed. Participants were allowed to manipulate and rotate artifacts to their best fit. To facilitate comparisons, all

experiments involved an orthogonal motion regardless of the material being processed. After the experiments, all tools were cleaned in an ultrasonic tank with natural soap at 15-minute intervals.

2.3. *Methods*

To avoid adopting the unwarranted functional connotation of the term ‘pitted anvil’, here we prefer to use the term ‘pitted stone’, and ‘depression’ is used to describe the concavity present on any of the surfaces of the cobbles. Following Adams et al., (2009), ‘pit’ is used when referring to microscopic concavities in association with battered areas and/or the inner zones of the depression. In addition, we documented other percussive marks such as impact points (i.e., individual strikes by thrusting percussion), battered areas (defined as clusters of superposed impacts), and percussive fractures (negative scars developed by the detachment of fragments from the blanks).

All pitted stones (archaeological and experimental) were analyzed macroscopically to characterize their technological attributes, and then georeferenced using Geographic Information System (GIS) techniques to compute general dimensions of the depressions, including area, perimeter, maximum length, and width. Depression orientation was also calculated using GIS. In this case, to ensure greater accuracy objects were oriented to their maximum axis using the option ‘rectangle_by_width’ (RbW) of ArcMap 10.4.1 (ESRI, 2015). Two orientation parameters were measured subsequently: (i) the orientation of the longest side of the depression resulting from a rectangle (RbW); and (ii) the orientation of the imaginary line connecting the antipodal pairs (‘convex_hull’, CH).

After the initial analysis, 24 of the 29 archaeological objects were selected for microscopic analysis using a low magnification approach, which has proven effective for

the characterization of use-wear traces in pounding tools (Rowe, 1995; Roda et al., 2012; Arroyo and de la Torre, 2016, 2018; Caricola et al., 2018). Analysis was made using a Leica S8APO with a magnification range between 1× and 8×, equipped with 10× ocular lenses, fiber optic illumination, and a Leica EC3 digital camera. It was noted that some tools presented a thin layer of concretion or sediment adhered to their surfaces and, occasionally, residues of the lacquer used by the original excavators when labeling the artifacts. To ensure that the tools were maintained as they were originally curated, we decided not to alter these conditions, and so they were only rinsed with water. Microscopic analysis focused on the identification of marks produced by fatigue (fractures, cracks, pits, grain crushing) and abrasive mechanisms (linear traces, leveling, and grain rounding; Adams, 2002; Adams et al., 2009).

Additionally, 24 pitted stones were 3D scanned using a Next Engine laser scanner at a macro mode (with a 0.0025" triangle size, 160k (1×) points/IN²), obtaining models with a resolution of 0.1 mm. 3D models were then used to compute morphological parameters of the artifacts such as volume and surface area, and processed using GIS techniques following procedures proposed by Caruana et al. (2014) and Benito-Calvo et al. (2015). Point clouds were imported into ArcMap 10.4.1 (ESRI, 2015), rasterized and transformed into digital elevations models (DEM), and used to obtain geomorphometric parameters such as the elevation relief ratio (Pike and Wilson, 1971; Szypula, 2017), also known as topographic position index (TPI; Caruana et al., 2014), and the slope of depressions. To ensure greater accuracy when measuring the slope, the analysis was performed only across the depressions and their adjacent area using the ArcMap function 'extracting by mask', which allows obtaining specific areas of a DEM.

Quantitative and spatial distribution analysis of depressions was performed using ArcMap 10.4.1 (ESRI, 2015), following protocols by de la Torre et al., (2013). Statistical

analysis was carried out using PAST (Hammer et al., 2001) and SPSS 22 (IBM, 2013). To test intra and intersite variations, a combination of non-parametric (Mann-Whitney U and Kruskal-Wallis) and Pearson correlation tests were used to process numerical data, and Chi-square for categorical data. In each statistical test, the significance threshold was assessed at a 0.05 significance level.

3. Results

3.1. Technological analysis of archaeological pitted stones

Apart from one pitted stone on a quartzite tabular block, the rest were made on lava cobbles ($n = 28$). Raw materials included trachyte ($n = 11$), basalt ($n = 12$), vesicular basalt ($n = 4$), quartzite ($n = 1$), and ignimbrite ($n = 1$). Preservation was generally good, other than four tools highly affected by weathering processes that had abraded their surfaces.

As shown in Table 2 and Figure 4, all pitted stones shared similar dimensions, with an average length of 84.90 mm (SD = 14.13 mm), mean weight of 356.32 g (SD = 174.75 g), an average volume of 166.60 cm³ (SD = 86.95 cm³), and a mean surface area of 163.43 cm² (SD = 59.30 cm²; Table 2). Similarities between their morphological characteristics are also shown in the surface-area-to-volume ratio, exhibiting overall high ratios (SA:V > 1 cm⁻¹), and density values normally over 2 g/cm³. Statistical comparison of metrics (length, width and weight) showed no significant differences between sites (Kruskal-Wallis $p > 0.05$ in all variables), nor differences when comparing pitted stones from Bed III and Bed IV (Mann-Whitney U test, asymptotic significance (2-tailed) $p > 0.05$ for the three variables).

Fourteen objects (48.3%) bore depressions on one horizontal face, twelve (41.4%) had depressions on two horizontal faces, and three artifacts (10.3%) had three or more

faces with depressions. Twelve pitted stones showed additional use-wear traces on distal ends and/or lateral planes of the cobbles, indicating that they were reoriented during their use in order to utilise additional regions of the cobbles. Battered areas were identified on fifteen (51.7%) pitted stones, four (13.8%) had impacts on their surfaces, and another four (13.8%) presented fracture scars ($n = 8$). Six of these fracture scars showed morphologies similar to fracture patterns recognized in knapping hammerstones (Hansen et al., 2009; authors' observation); one of them was a transversal fracture that split the original cobble into two halves, and one fracture was located on a lateral plane. None of the analyzed pitted stones were reused as cores, thus maintaining their function as pounding tools until they were discarded. Interestingly, in most cases, pitted horizontal planes exhibited no other percussive marks, indicating that the depressions were formed via a controlled orthogonal motion, in which there were neither major displacements of the objects processed nor missed impacts (i.e., they were produced by the contact between the active and passive elements).

3.2. *Microscopic characterization, spatial distribution, and quantification of depressions*

The 29 pitted stones analyzed here contain a total of 50 depressions on their surfaces. We determined that eight depressions were formed by the connection of, at least, two originally separate pits, while one pitted stone bore two separate depressions on the same horizontal plane. Microscopic observations revealed no evidence of use-wear marks associated with grinding or friction gestures such as striations. Instead, visible modifications could have been associated with a thrusting percussion motion.

Figure 5 summarizes the microscopic traces identified on the pitted stones. The overall grain structure of the pitted stones was amalgamated, with only a few tools showing a continuous grain distribution pattern. Inner areas of pits tend to be irregular

and/or sinuous, resulting from microfracturing, and grain detachment during the formation of depressions. The presence of substantial abrasion traces on the surfaces of the four tools was, most likely, not due to use but to taphonomic alteration in the fluvial context in which artifacts were recovered. Grain rounding inside the depressions is also common, although it was difficult to determine whether such rounding was produced through tool use or by postdepositional processes. Grain leveling was also recognized in the inner area of depressions in five tools, which is suggestive of a compressive force during depression development. Grain microfractures and crushing were the most common microscopic modifications of the inner areas of the depressions (Fig. 6). Depressions in nine of the tools exhibited V-shaped incisions (<5 mm long) along their rims (Fig. 6K, L).

Forty-eight depressions had well-defined outlines and therefore were suitable for further analysis using GIS spatial distribution protocols (de la Torre et al., 2013). Overall, depressions had a mean area of 4.90 cm² (SD = 3.61 cm²) and a mean perimeter of 8.55 cm (SD = 3.21 cm). The mean percentage of the tool area covered by depressions (PA index) was 10.41% (SD = 7.09%), and depressions tended to be centred on the horizontal plane, as supported by the low distance between the centre of the object and the depression centre (mean DAC-DC = 0.60 cm; SD = 0.38 cm; see Table 3 and Supplementary Online Material [SOM] Table S1).

Additionally, depression orientations were calculated using the minimum bounding geometry (MBG) index (Fig. 7A). Results of the MBG analysis demonstrated that depressions had a preferential oblique orientation (Fig. 7B, C). When only taking the CH orientation into account, another set of depressions were oriented nearly parallel to the longest axis of the tool (Fig. 7C).

Furthermore, a sample of 31 horizontal faces (from 23 lava tools) with depressions were selected for 3D analysis. The elevation relief ratio confirmed our initial identification of the depressions through changes on the elevation of the surfaces of the pitted stones, in which the higher values match with the rims of the depressions (Fig. 8), and point at the uniformity of the rest of the surfaces. Based on the maximum slope of the depressions (SOM Table S2), three types of depressions were differentiated: (1) shallow depressions (maximum slope ranging between 20° and 50°, $n = 9$); (2) medium-slope depressions (maximum slope between 30° and 65°, $n = 14$); and (3) tools with steep depressions (maximum slope between 40° and 80°, $n = 8$). It was also noted that, in those tools with shallow depressions, the maximum slope tends to be evenly distributed across the depression (Fig. 9A). In contrast, in medium-slope and steep depressions the maximum slope values tend to be localized and have an uneven distribution across the depressions (Fig. 9B, C), indicating that during depression formation there were specific areas of the surfaces that received a more incisive force than others.

Macroscopic results showed that smaller depressions usually have sharp rims, while these are smoother in larger depressions. To determine whether the size of the depression has a significant influence on the slope, Pearson correlation tests were made comparing the area, perimeter and PA of depressions against their maximum, minimum and mean slope. Results in Table 4 indicate no correlation between morphological variables (i.e., area and PA index) and the slope ($p > 0.05$), and only the perimeter of the depression correlated with the minimum ($r = 0.366$, $n = 31$, $p = 0.043$) and mean slope ($r = 0.391$, $n = 31$, $p = 0.029$).

A diachronic comparison on the morphological attributes of those depressions, computed using GIS techniques (area, perimeter, length, DAC-DC and PA), showed no significant differences between Bed III and IV pitted stones (Mann-Whitney U test,

Asymp. Sig (2-tailed) $p > 0.05$ in all variables). These results on morphometrics of the depressions, alongside morphological similarities of use wear traces, blank type and associated artefacts, all suggest that pitted stone function remained stable through time.

3.3. Experimental materials

3.3.1. Bipolar knapping The results of our bipolar flaking experiment (Exp #30) are consistent with similar experimental studies reporting quick formation of depressions on pounding tools (Le Brun-Ricalens, 1989; Jones, 1994; Donnart et al., 2009; de la Peña Alonso, 2011; de la Peña Alonso and Vega Toscano, 2013; Roda et al., 2012). In our experiment, the anvil developed an incipient depression with a measured area of 16.23 cm², irregular in section, delineated by battering marks and scattered impact points that show crushed and microfractured grains (Table 5; Fig. 10A-C). Anvil use-wear marks were formed by the impact against the core, and their large distribution across the surface was related to the large surface of the core, a pattern consistent with our previous experimental results (de la Torre et al., 2013). The hammerstone underwent substantial modification over the two horizontal planes and on the distal end, as it was re-oriented during the experiment. One horizontal plane showed a concentrated area of heavy battering (measuring 10.52 cm²), while on the opposing plane and one distal end, heavily battered marks formed an incipient depression measuring 12.31 cm². The hammerstone also presented isolated striations that were formed through friction against the core. Based on their slope values, depressions in both the hammerstone and the anvil can be classified within the shallow depression group (maximum slope range between 20° and 45°) described above.

3.3.2. Flake splitting The first stage of this experiment (Exp #32) consisted of free-hand flake production from a quartzite block. During this phase, the lava hammerstone

developed two battered areas on the lateral sides, and one percussion positive was detached (Fig. 11A). Consequently, seven complete flakes were analyzed before being used in the second stage of the experiment, which involved flake splitting. During this second phase, the distal end of the flakes was placed on the anvil and flake-striking platforms were struck with a hammerstone. This process promptly caused depression development on the surface of the anvil (Fig. 10D) and the hammerstone (Fig. 11A). These depressions exhibited inner areas with crushed grains and microfractures with the formation of isolated and scattered linear traces (Fig. 11B-D), smaller than those developed during bipolar flaking. Hammerstone and anvil depressions produced during flake splitting had a mean area of 5.73 cm², mean perimeter of 10.54 cm, low PA index (mean PA = 6.01%; see details in SOM Table S1), and showed slopes ranging between 30° and 65°, therefore sharper than depressions formed during bipolar flaking.

3.3.3. Nut-cracking Processing nuts using two lava cobbles (Exp #31) was less straightforward than in previous experiments using quartzite anvils (de la Torre et al., 2013). The nuts were difficult to stabilize on the anvil and frequently rolled away before and/or after the striking motion. Tools did not develop any depressions, despite their intense use during nut-cracking (see Table 1). The most conspicuous use-wear marks were similar in both tools and consisted of clusters of impacts on the peripheral areas of the tools produced by the contact between the anvil (Fig. 10G) and the hammerstone (Fig. 11E). Under the microscope (Table 5) we identified crushed and microfractured grains (Fig. 11F-I), which were produced primarily by the contact between the hammer and the anvil, as was also noted in an earlier experimental programme with quartzite (de la Torre et al., 2013). In addition to grain-crushing and microfracturing, the surface where the nuts were placed became slightly altered by tribochemical dissolution, produced by

compression forces and oil residues during nut cracking, a process that has also been observed elsewhere (e.g., Adams, 1988; Roda et al., 2012).

3.4. Comparison of archaeological and experimental assemblages

Significant differences exist between the length, width, and weight (Mann-Whitney U test, asymptotic significance (2-tailed) $p < 0.05$ in the three variables) of the archaeological and (larger- sized) experimental artifacts (Table 2). However, these differences are clearly biased by the raw material selection of cobbles for the experiments. More interestingly, no significant differences were found in the percentage of tool surface covered by depressions (PA index), or in DAC-DC (distance between the tool center and the depression center (Mann-Whitney U test, asymptotic significance (2-tailed) $p > 0.05$ on both indexes) between the archaeological and experimental tools, despite size disparities in the two samples. On the contrary, there were significant differences when depression areas (D Area) and their maximum lengths and perimeters were compared (Mann-Whitney U test, asymptotic significance (2-tailed) $p < 0.05$): depressions produced during experimental bipolar flaking tended to be larger than most of the depressions identified in the archaeological pitted stones.

Morphological differences were observed in the depressions formed during experimental bipolar flaking and flake splitting. Hammerstone and anvil depressions created during flake splitting are steep, have an elongated morphology and higher incidence on the surface, while bipolar knapping depressions tend to be irregular in shape and have smoother slopes. We interpret this pattern as being caused by cores having a wider surface in contact with the anvil during bipolar flaking, since cores tend to absorb and spread the force transmitted by the hammer across the surface. On the other hand, flakes are thinner, and when they are struck during flake splitting, their distal ends tend

to act like wedges, forming depressions more rapidly than during bipolar flaking. Jones (1994) also noted such features and argued that elongated morphologies on the depressions were related to the different ways in which cobbles were held during bipolar flaking.

Both the archaeological and the flake splitting experimental assemblages presented similar use-wear traces, with crushing and grain microfracturing commonly found within the depressions. Shape and depth of depressions were particularly similar between the archaeological tools and the experimental tools used to split flakes; both display angular incisions around the rims of depressions running towards their inner areas (Fig. 6L), which we attribute to friction with angular objects (i.e., a flake). Interestingly, such traces were completely absent in the experimental nut-cracking tools. With regards to the orientation of depressions, some similarities can also be observed: although depressions were not developed in lava pounded tools, other nut-cracking experiments using more friable materials such as sandstone have resulted in depressions with a circular morphology (Rowe, 1995).

4. Discussion

4.1. Pounding or stone flaking: what were Beds III and IV pitted stones used for?

Our analysis indicates that the depressions on pitted stones from Beds III and IV were formed via controlled motions in which the target was hit with precision. The absence of wear traces other than depressions in 48.3% ($n = 14$) of the analyzed tools suggests that they were used for a specific task. In addition, the fact that, overall, cobbles were not highly modified supports the hypothesis they were used for a short period of time. Based on the morphology and wear traces discussed above, we propose that depressions were formed mostly through thrusting percussion motions, with no grinding,

diffused resting percussion, or drilling motions. Occasionally, pitted stones were flipped and/or re-oriented for further use.

While the findings above are important for the reconstruction of the actions involved in the use of Beds III and IV pitted stones, such observations alone cannot determine if the pitted stones were used during flaking, pounding, or both. Assessing whether pitted stones were used as active or passive elements based on their dimensions is challenging. Their average size (Table 2) would allow them all to be handheld, contrary to large, clearly stationary anvils such as many of those in Bed II (Mora and de la Torre, 2005). Use-wear is therefore potentially more informative than dimensions in the case of Beds III and IV pitted stones. As shown in Figure 12, percussive traces on lateral and distal ends, as well as percussive fractures, indicate that some of the cobbles were used as active elements, probably as regular knapping hammerstones. For example, in the case of Figure 12A, the artifact was used as an active element after the formation of the depressions, as the fractures are nearly overlapping the pit. Nonetheless, polyvalent use of some pitted stones as knapping hammerstones has not yet allowed us to identify the tasks involved in the formation of depressions.

Pitted stones have frequently been associated with bipolar knapping activities (Leakey and Roe, 1994; Jones, 1994; Donnart et al., 2009; Roda et al., 2012), but it has also been reported that depressions are not always formed when conducting bipolar flaking, and that such formation is raw material-dependent (de la Torre et al., 2013). Additionally, it has been proposed that pitted stones co-occur with outils écaillés (MacDonald, 1968) and/or bipolar cores (Hayden, 1980; Roda et al., 2015). Based on Leakey and Roe's (1994) report (Table 6), it seems that there are no significant intersite differences in the distribution of pitted stones ($\chi^2 = 2.818$, $df = 7$, $p = 0.901$) and punches/outils écaillés ($\chi^2 = 1.273$, $df = 8$, $p = 0.996$) and, indeed, there is a statistically

significant correlation between both groups (Pearson's correlation $r = 0.621$, $n = 11$, $p = 0.041$). Such correlation, however, is not that obvious when considering absolute frequencies of both groups of artifacts. For example, the Ferruginous Sand layer at JK yielded the largest collection of pitted stones ($n = 11$ according to Leakey and Roe, 1994; $n = 8$ in this study), and yet there is a low number of punches and outils écaillés ($n = 3$). Determining the function of punches and outils écaillés also requires further analysis; Jones (1994) hypothesized that they could have been used as wedges, but this remains to be experimentally replicated and tested on the archaeological material.

Our experiments indicate that flake splitting may explain the elongated morphologies in some of the archaeological depressions. Additionally, we observed that some of the artefacts originally classified by Mary Leakey as subspheroids (Fig. 13) may instead be cores reduced through a bipolar technique which, although not necessarily involved in the same gestures as flake splitting, is consistent with the use of pitted stones in lithic reduction tasks.

Alternative uses of pitted stones in other activities also merit further discussion. Primatological (e.g., Tan et al., 2015; Haslam et al., 2013, 2016) and archaeological (Strudwick, 1995) reports indicate that pounding tools used in gastropod processing also develop depressions. At Olduvai Gorge, edible freshwater bivalves (*Chambardia wahlbergi*, *Mutela* spp. and *Unio* spp.) have been identified in Beds III and IV (Hay, 1976; Leakey 1965; Leakey and Roe, 1994; Johnson et al., 2016). However, this evidence is circumstantial, and bivalves are yet to be reported in association with the lithic assemblages.

Pitted stones associated with nut-cracking activities are documented among living primates such as chimpanzees (Kortlandt, 1986) and capuchin monkeys (Visalberghi et al., 2007). Chimpanzee pitted stone depressions tend to be elongated or circular in shape

and have smooth inner areas, as a result of a process of plastic deformation during percussive motions (Benito-Calvo et al., 2015). However, direct comparisons between chimpanzee and Olduvai pitted stones are challenging due to the substantial differences in the raw material used which, as shown in the case of Bossou rocks (Benito-Calvo et al., 2015) and Olduvai quartzite (Arroyo et al., 2016), is essential to explain disparities in use-wear formation across nut-cracking anvils.

Gesher Benot Ya'aqov (GBY) in Israel at 0.78 Ma (Goren-Inbar et al., 2000) is roughly coeval to Olduvai Bed IV, and a substantial assemblage of pitted stones have been unearthed from different archaeological units (Goren-Inbar et al., 2002), where seven types of aquatic and terrestrial nuts were also documented (Goren-Inbar et al., 2014). Depressions in GBY pitted stones are described as concavities with a round morphology and smooth inner surfaces (Goren-Inbar et al., 2002), which resemble some of those we identified in the Olduvai sample (Fig. 6A).

Based on our experimental results and the review of the rather limited primatological and archaeological evidence, our technomorphological, microscopic, and spatial analyses of use-wear concurs with Jones' (1994) initial claim that Beds III and IV pitted stones were probably involved in bipolar and flake splitting tasks, although we cannot exclude the possibility that they were also used to process organic materials. The latter hypothesis, however, will require the application of appropriate protocols for residue analysis and high magnification use-wear analysis during the next phase of research.

The scarcity of pitted stones in the ESA record may be due to specialization of activities involved, as is the case of nut-cracking at GBY. The fact that Beds III and IV contain the largest collection of pitted stones in the Olduvai sequence has implications for modelling hominin activities. Working under the assumption that pitted stones were

used exclusively to split flakes and in bipolar knapping activities, it would lend support to recent observations of the increase of bipolar knapping from Lemuta times onwards at Olduvai Gorge (de la Torre and Mora, 2018). Given the size of the pitted stones in Beds III and IV, it is probable that pitted stones were involved in the reduction of small cores (potentially no larger than 5 cm) and/or the manufacture of split flakes. Thus, during this particular interval within the Olduvai sequence, it seems likely that hominins were not focusing exclusively on the manufacture of the large cutting tools typical of the East African Acheulean, but also on the production of small bipolar flakes, and outils écaillés/punches (Fig. 13) whose function remains unknown.

5. Conclusions

The function of pitted stones has been widely discussed in late prehistoric periods (e.g., de Beaune, 1993; Holst, 2010; Roda et al., 2012) but, to date, no systematic use-wear studies existed to unravel their functional role in the early Pleistocene record. At Olduvai Gorge, the importance of pitted stones increased considerably during Acheulean times in Bed III and especially in Bed IV, maintaining consistent morphological and use-wear features throughout the sequence. Our spatial and morphometric analysis reveals that depressions tend to have a centred location on the surface of the tool and an oblique orientation. The identification of crushed grains and other microscopic traces such as pits and grain microfractures indicates that depressions were formed by a thrusting percussion motion. Depressions and additional battering marks on various faces of the blanks further suggest an occasional change of the working surface and reorientation of the tool during use.

Our experiments have demonstrated that depressions formed during flake splitting have similar morphological characteristics to those observed in some of the

archaeological pitted stones. Future studies of the Olduvai Beds III and IV sites should re-examine the overall technological characteristics of the lithic assemblages and evaluate the importance of bipolar knapping among flaked and detached pieces. Our spatial, morphological and microwear results are in agreement with Jones' (1994) macroscopic experimental observations about the use of pitted stones in bipolar and flake splitting activities, although we report smooth morphologies in some of the depressions suggestive of potential additional uses, and therefore, a multifunctional character for these battering objects cannot not be excluded.

Our study is the first to revisit Olduvai Beds III and IV pounded artifacts since Jones' (1994) work, and the application of new techniques such as GIS and 3D surface analysis as well as microscopic analysis, contributes to move forward in both the enhancement of analytical techniques and our understanding of controversial ESA tool types. However, we would like to stress that, if caution should be exerted against single explanatory models for prehistoric tools in general, pitted stones are still particularly poorly known artifacts, and functional assumptions must be considered with extra care.

Given the general paucity of pitted stones in the Early Stone Age record worldwide, their conspicuous presence in the Beds III and IV assemblages at Olduvai Gorge, and their technomorphological and microwear consistency across this sequence, this group of artifacts is particularly valuable for the identification of the variety of activities carried out during the time of *Homo erectus*. Previous analysis of Olduvai Bed I and II pounding tools (Mora and de la Torre, 2005; Arroyo and de la Torre, 2016, 2018), has showed that interassemblage differences may be indicative of the high variability in landscape use by Acheulean hominins. The higher presence in Beds III and IV of pitted stones, bipolar flaking, and the associated outils écaillés indicates novel strategies in hominin activity patterns, potentially related to the exploitation of new resources, and can

be considered as an adaptative response to the environmental changes that took place in the region during the Early and Middle Pleistocene.

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References

- Adams, J., 1988. Use-wear analyses on manos and hide-processing stones. *Journal of Field Archaeology* 15, 307-315.
- Adams, J., 2002. Mechanisms of wear on ground stone surfaces. In: Procopiu, H., Treuil, R. (Eds.), *Moudre et broyer: l'interprétation fonctionnelle de l'outillage de mouture et de broyage dans la préhistoire et l'antiquité*. CTHS, Paris, pp. 57-68.
- Adams, J., Delgado, S., Dubreuil, L., Hamon, C., Plisson, H., Risch, R., 2009. Functional analysis of macro-lithic artefacts: a focus on working surfaces. In: Costa, L.J., Eigeland, L., Sternke, F. (Eds.), *Non-flint Raw Material Use in Prehistory: Old*

548   Prejudices and New Directions. Proceedings of the XV. Congress of the U.I.S.P.P,
549   Archaeopress, Oxford, pp. 43-66.

550   Akerman, K., 1975. Aboriginal camp sites on the western coast of Dampier Land, western
551   Australia. Occasional Papers in Anthropology 4, 93-104.

552   Arroyo, A., de la Torre, I., 2018. Pounding tools in HWK EE and EF-HR (Olduvai Gorge,
553   Tanzania): Percussive activities in the Oldowan-Acheulean transition. Journal of
554   Human Evolution 120, 402-421.

555   Arroyo, A., Hirata, S., Matsuzawa, T., de la Torre, I., 2016. Nut cracking tools used by
556   captive chimpanzees (*Pan troglodytes*) and their comparison with Early Stone
557   Age percussive artefacts from Olduvai Gorge, PLoS One 11, e0166788.

558   Arroyo, A., de la Torre, I., 2016. Assessing the function of pounding tools in the Early
559   Stone Age: A microscopic approach to the analysis of percussive artefacts from
560   Beds I and II, Olduvai Gorge (Tanzania). Journal of Archaeological Science 74,
561   23-34.

562   Benito-Calvo, A., Carvalho, S., Arroyo, A., Matsuzawa, T., de la Torre, I., 2015. First
563   GIS analysis of modern stone tools used by wild chimpanzees (*Pan troglodytes*
564   *verus*) in Bossou, Guinea, West Africa. PLoS One 10, e0121613.

565   Boshier, A.K., 1965. Effects of Pounding by africans of North-West Transvaal on hard
566   and soft stones. The South African Archaeological Bulletin 20, 131-136.

567   Britt, C., 1973. Historical evidence for a use of cupstones. Ohio Archaeologist 23, 26-27.

568   Brock, A., Hay, R.L., Brown, F.H., 1972. Magnetic stratigraphy of Olduvai Gorge and
569   Ngorongoro, Tanzania. Geological Society of America 4, 457.

570   Caricola, I., Zupancich, A., Moscone, D., Mutri, G., Falcucci, A., Duches, R., Peresani,
571   M., Cristiani, E., 2018. An integrated method for understanding the function of

572 macro-lithic tools. Use wear, 3D and spatial analyses of an Early Upper
573 Palaeolithic assemblage from North Eastern Italy. PLoS One 13, e0207773.

574 Caruana, M.V., Carvalho, S., Braun, D.R., Presnyakova, D., Haslam, M., Archer, W.,
575 Bobe, R., Harris, J.W.K., 2014. Quantifying traces of tool use: A novel
576 morphometric analysis of damage patterns on percussive tools. PLoS One 9,
577 e113856.

578 Cerling, T.E., Hay, R.L., 1986. An isotopic study of paleosol carbonates from Olduvai
579 Gorge. Quaternary Research 25, 63-78.

580 Chavaillon, J., 1979. Essai pour une typologie du matériel de percussion. Bulletin de la
581 Société Préhistorique Française 76, 230-233.

582 Chavaillon, J., 2004. The site of Gombore I. Discovery, geological introduction and study
583 of percussion material and tools on pebble. In: Chavaillon, J., Piperno, M. (Eds.),
584 Studies on the Early Paleolithic site of Melka Kunture, Ethiopia. Istituto italiano
585 di preistoria e protostoria, Florence, pp. 253-369.

586 Crabtree, D.E., 1972. An introduction to flint working. Idaho Museum of Natural History,
587 Idaho.

588 de Beaune, S.A., 1989. Essai d'une classification typologique des galets et plaquettes
589 utilisés au Paléolithique. Gallia Préhistoire 31, 27-64.

590 de Beaune, S.A., 1993. Approche expérimentale de techniques paléolithiques de
591 façonnage de roches peu aptes à la taille. Paléo 5, 155-177.

592 de la Peña Alonso, P., 2011. Sobre la identificación macroscópica de las piezas astilladas:
593 propuesta experimental. Trabajos de Prehistoria 68, 79-98.

594 de la Peña Alonso, P., Vega Toscano, L. G., 2013. Bipolar knapping in Gravettian
595 occupations at El Palomar rockshelter (Yeste, Southeastern Spain). Journal of
596 Anthropological Research 69, 33-64.

597 de la Torre, I., Benito-Calvo, A., Arroyo, A., Zupancich, A., Proffitt, T., 2013.
 598 Experimental protocols for the study of battered stone anvils from Olduvai Gorge
 599 (Tanzania). *Journal of Archaeological Science* 40, 313-332.
 600 de la Torre, I., Mora, R., 2005. Technological strategies in the lower Pleistocene at
 601 Olduvai Beds I & II. *Eraul*, Liège.
 602 de la Torre, I., Mora, R., 2018. Oldowan technological behaviour at HWK EE (Olduvai
 603 Gorge, Tanzania). *Journal of Human Evolution* 120, 236-273.
 604 Deishler, H.K., 1939. Pitted stones or problem of the pitted stones. *The Pennsylvania*
 605 *Archaeologist* 9, 11-12.
 606 Donnart, K., Naudinot, N., Le Clézio, L., 2009. Approche expérimentale du débitage
 607 bipolaire sur enclume: caractérisation des produits et analyse des outils de
 608 production. *Bulletin de la Société Préhistorique Française* 106, 517-533.
 609 Gentry, A.W., Gentry, A., 1978. Fossil bovidae (*Mammalia*) of Olduvai Gorge, Tanzania,
 610 Part 2. *Bulletin of the British Museum (Natural History) Geological Series* 30, 1-
 611 83.
 612 Goren-Inbar, N., Feibel, C.S., Verosub, K.L., Melamed, Y., Kislev, M.E., Tchernov, E.,
 613 Saragusti, I., 2000. Pleistocene milestones on the out-of-Africa corridor at Gesher
 614 Benot Ya'aqov, Israel. *Science* 289, 944-947.
 615 Goren-Inbar, N., Melamed, Y., Zohar, I., Akhilesh, K., Pappu, S., 2014. Beneath still
 616 waters - Multistage aquatic exploitation of *Euryale ferox* (*Salisb.*) during the
 617 Acheulian. *Internet Archaeology* 37, <https://doi.org/10.11141/ia.37.1>.
 618 Goren-Inbar, N., Sharon, G., Melamed, Y., Kislev, M.E., 2002. Nuts, nut cracking, and
 619 pitted stones at Gesher Benot Ya'aqov, Israel., *Proceedings of the National*
 620 *Academy of Sciences USA* 99, 2455-2460.

621 Gumert, M.D., Kluck, M., Malaivijitnond, S., 2009. The physical characteristics and usage
622 patterns of stone axe and pounding hammers used by long-tailed macaques in the
623 Andaman Sea Region of Thailand. *American Journal of Primatology* 71, 549-608.

624 Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. PAST: Paleontological statistics software
625 package for education and data analysis. *Palaeontologia Electronica* 4, 4.

626 Hansen, E., Eigeland, L., 2009. The rock that rocks the rock. An experimental study with
627 hammerstones. In: Sternke, F., Costa, L.J., Eigeland, L. (Eds.), *Non-flint Raw*
628 *Material Use in Prehistory: Old Prejudices and New Directions*. Proceedings of
629 the XV. Congress of the U.I.S.P.P. Archaeopress, Oxford, pp. 69-75.

630 Haslam M., Gumert M.D., Biro D., Carvalho S., Malaivijitnond S., 2013 Use-wear
631 patterns on wild macaque stone tools reveal their behavioural history. *PLoS One*
632 8, e72872.

633 Haslam, M., Luncz, L.V., Pascual-Garrido, A., Falótico, T., Malaivijitnond, S., Gumert,
634 M.D., 2016. Archaeological excavation of wild macaque stone tools. *Journal of*
635 *Human Evolution* 96, 134-138.

636 Hay, R.L., 1963. Stratigraphy of Beds I through IV, Olduvai Gorge, Tanganyika. *Science*
637 139, 829-833.

638 Hay, R.L., 1976. *Geology of the Olduvai Gorge: a study of sedimentation in a semiarid*
639 *basin*. University of California Press, Berkeley.

640 Hay, R.L., 1994. Geology and dating of Beds III and IV and the Masek Beds. In: Leakey,
641 M.D., Roe, D.A. (Eds.), *Olduvai Gorge. Vol. 5. Excavations in Beds III, IV and*
642 *the Masek Beds, 1968-1971*. Cambridge University Press, Cambridge, pp. 8-14.

643 Hayden, B., 1980. Confusion in the bipolar world: bashed pebbles and splintered pieces.
644 *Lithic Technology* 9, 2-7.

645 Holst, D., 2010. Hazelnut economy of early Holocene hunter-gatherers: a case study from
 646 Mesolithic Duvensee, northern Germany. *Journal of Archaeological Science* 37,
 647 2871-2880.

648 IBM Corp., 2013. IBM SPSS Statistics for Windows, Version 22.0. Armonk, New York.

649 Johnson, C.C., Njau, J.K., Van Damme, D., Schick, K., 2016. Paleoecologic significance
 650 of malacofauna, Olduvai Gorge, Tanzania. *Palaios* 31, 319-326.

651 Jones, P.R., 1994. Results of experimental work in relation to the stone industries of
 652 Olduvai Gorge. In: Leakey, M.D., Roe, D.A. (Eds.), *Olduvai Gorge. Excavations*
 653 *in Beds III, IV and the Masked Beds, 1968-1971*. Cambridge University Press,
 654 Cambridge, pp. 254-298.

655 Kleindienst, M.R., 1964. Summary report on excavations at site JK 2, Olduvai Gorge,
 656 Tanganyika, 1961-1962, Appendix 2. Annual report of the Antiquities Division
 657 for the year 1962, pp. 4-6.

658 Kleindienst, M.R., 1973. Excavation at the JK2, Olduvai Gorge, Tanzania, 1961-1962:
 659 the geological setting. *Quaternaria* 17, 145-208.

660 Kortlandt, A., 1986. The use of stone tools by wild-living chimpanzees and earliest
 661 hominids. *Journal of Human Evolution* 15, 77-132.

662 Kuhn, S., Stiner, M.C., Güleç, E., Yilmaz, H., Baykara, I., Açikkol, A., Goldberg, P.,
 663 Martinez Molina, K., Ünay, E., Suata-Alpaslan, F., 2009. The early Upper
 664 Paleolithic occupations at Üçağızlı Cave (Hatay, Turkey). *Journal of Human*
 665 *Evolution* 56, 87-113.

666 Le Brun-Ricalens, F., 1989. Contribution à l'étude des pièces esquillées: la présence de
 667 percuteurs à "cupules". *Bulletin de la Société Préhistorique Française* 86, 194-211.

668 Leakey, L.S.B., 1954. Olduvai Gorge. *Scientific American* 190, 66-71.

669 Leakey, L.S.B., 1965. Olduvai Gorge 1951–61, Volume 1: A Preliminary Report on the
670 Geology and Fauna. Cambridge University Press, Cambridge

671 Leakey, L.S.B., Hopwood, A.T., Reck, H., 1931. New yields from the Oldoway bone
672 beds, Tanganyika territory. *Nature* 128, 1075.

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

675 Leakey, M.D., Roe, D.A., 1994. Olduvai Gorge. Vol. 5. Excavations in Beds III, IV and
676 the Masek Beds, 1968-1971. Cambridge University Press, Cambridge.

677 Luncz, L.V., Proffitt, T., Kulik, L., Haslam, M., Wittig, R.M., 2016. Distance-decay effect
678 in stone tool transport by wild chimpanzees. *Proceedings of the Royal Society B*
679 293, 20161607.

680 MacDonald, G., 1968. Debert: A Paleo-Indian site in central Nova Scotia. National
681 Museum of Canada. Ottawa.

682 Maguire, B., 1965. Foreign pebble pounding artefacts in the breccias and the overlying
683 vegetation soil at Makapansgat limeworks. *The South African Archaeological*
684 *Bulletin* 20, 117-130.

685 Manega, P., 1993. Geochronology, geochemistry and isotopic study of the Plio-
686 Pleistocene hominid sites and the Ngorongoro volcanic highland in Northern
687 Tanzania. Ph.D. Dissertation, University of Chicago, Boulder.

688 Mora, R., de la Torre, I., 2005. Percussion tools in Olduvai Beds I and II (Tanzania):
689 Implications for early human activities. *Journal of Anthropological Archaeology*
690 24, 179-192.

691 Pardoe, C., Fullagar, R., Hayes, E., 2019. Quandong stones: A specialised Australian nut-
692 cracking tool. *PLoS One* 14, e0222680.

693 Pike, R.J., Wilson, S.E., 1971. Elevation-relief ratio, hyposometric integral, and
694 geomorphic area-altitude analysis. Geological Society of America Bulletin 82,
695 1079-1084.

696 Read, M.C., 1892. Archaeology of Ohio. The Western Reserve Historical Society,
697 Cleveland.

698 Roche, H., de la Torre, I., Arroyo, A., Brugal, J.-P., Harmand, S., 2018. Naiyena Engol 2
699 (West Turkana, Kenya): a case study on variability in the Oldowan. African
700 Archaeological Review 35, 57-85.

701 Roda Gilabert, X., Martínez-Moreno, J., Mora, R., 2012. Pitted stone cobbles in the
702 Mesolithic site of Font del Ros (Southeastern Pre-Pyrenees, Spain): some
703 experimental remarks around a controversial tool type. Journal of Archaeological
704 Science 39, 1587-1598.

705 Roda Gilabert, X., Mora, R., Martínez-Moreno, J., 2015. Identifying bipolar knapping in
706 the Mesolithic site of Font del Ros (northeast Iberia). Philosophical Transactions
707 of the Royal Society B 370: 20140354.

708 Rowe, R., 1995. Towards cupstone classification: an experimental approach. Ohio
709 Archaeologist 45, 217-238.

710 Santonja, M., Panera, J., Rubio-Jara, S., Pérez-González, A., Uribe Larrea, D., Domínguez-
711 Rodrigo, M., Mabulla, A.Z.P., Bunn, H.T., Baquedano, E., 2014. Technological
712 strategies and the economy of raw materials in the TK (Thiongo Korongo) lower
713 occupation, Bed II, Olduvai Gorge, Tanzania. Quaternary International 322-323,
714 181-208.

715 Strudwick, I., 1995. The multi-functional pitted stones of coastal California and their use
716 in marine shell processing. Proceedings of the Society for California Archaeology
717 8, 147-166.

- Struhsaker, T.T., Hunkeler, P., 1971. Evidence of tool-using by chimpanzees in the Ivory Coast. *Folia Primatologica* 15, 212-219.
- Szypula, B., 2017. Digital elevation models in geomorphology.. In: Shukla, D. P. (Ed.), *Hydro-Geomorphology - models and trends*. Intech Open. National and University Library in Zagreb, Croatia, pp 81-112.
- Tamrat, E., Thouveny, N., Taïeb, M., Opdyke, N.D., 1995. Revised magnetostratigraphy of the Plio-Pleistocene sedimentary sequence of the Olduvai Formation (Tanzania). *Palaeogeography, Palaeoclimatology, Palaeoecology* 114, 273-283.
- Tan, A., Hoon Tan, S., Vyas, D., Malaivijitnond, S., Gumert, M.D., 2015. There is more than one way to crack an oyster: identifying variation in Burmese long-tailed macaque (*Macaca fascicularis aurea*) stone-tool use. *PLoS One* 10, e0124733.
- Visalberghi, E., Frigaszy, D., Ottoni, E., Izar, P., de Oliveira, M.G., Andrade, F.R.D., 2007. Characteristics of hammer stones and anvils used by wild bearded capuchin monkeys (*Cebus libidinosus*) to crack open palm nuts. *American Journal of Physical Anthropology* 132, 426-444.
- Yamamoto, K., 1990. Space-time analysis of raw material utilization for stone implements of the Jomon culture in Japan. *Antiquity* 64, 868-889.

Figure captions

- Figure 1.** Schematic stratigraphy of the upper Beds at Olduvai Gorge (redrawn and adapted from Leakey and Roe, 1994,p. 3), and location of Beds III and IV sites. Ages follow Cerling and Hay (1986) and Manega (1993).
- Figure 2.** Example of pitted stones analysed in this study from JK (A-B) and WK (C-F).

Figure 3. General view of the experiments (A: bipolar knapping; B: nut-cracking; C: flake splitting) and the reference collection.

Figure 4. Box-and-whisker plots with dimensions (A-B), weight (C) and volume (computed from 24 tools with 3D models, D) of the pitted stones analyzed. Boxes represent interquartile range, whiskers indicate variability outside the upper and lower quartiles, and the outliers are represented by circles. The line crossing the boxes indicates the median.

Figure 5. Seriation with the use-wear marks identified in the archaeological pitted stones. The presence of sediment, concretion or lacquer on the inner areas of the depressions obstructed the identification of microscopic traces in six of them.

Figure 6. Percussive traces identified in archaeological pitted stones. A–E) WK (original ID not preserved): general view (A) and details of grain crushing (B, C; 80×, scales = 500 µm), pit and grain microfracture (D; 10×, scale = 3 mm), and the unmodified surface (E; 20×, scale = 2 mm). F–L) Pitted stone (HEB E 167): general view of the two horizontal planes (F) and close-up of the depression on face 1 (G). The inner area of this depression bears crushed grains (H, I: 63×, scale = 500 µm) and pits (J: 30×, scale = 1 mm). Some angular incisions were identified in face 2, associated with an incipient depression and battered areas (K: 10×, scale = 3 mm; L: 16×, scale = 2 mm). Note the amalgamated grain structure on this tool.

Figure 7. A) Example of a georeferenced pitted stone to calculate orientation of the depression and quantify use-wear traces. B, C) Rose diagram showing square-by-width orientation (B) and convex-hull orientation (C). Abbreviation: MGB = minimum bounding geometry.

Figure 8. Examples of surface relief ratios computed in four horizontal faces. Note that the highest values (closer to 1) corresponds to the ridges of depressions. Scale = 5 cm.

Figure 9. Morphometric classification based on the maximum slope identified in the depressions: A) 20–45°; B) 30–65°; C) 40–80°. Areas with maximum slope ranges are highlighted over the hillshaded elevation models. Note the location of maximum slopes in particular areas of the depressions. Scale = 5 cm.

Figure 10. Experimental passive elements. A–C) Blank used in bipolar flaking (O#69): general view (A); depression with crushed and microfracture grains (B; 10×, scale = 3 mm); crushed crystal (C; 40×, scale = 1 mm). D–F) Tool used to split flakes (O#246) with an elongated depression: general view (D); impact associated with grain crushing and microfracturing (E; 25×, scale = 2 mm); pit formed in a crushed area (F; 80×, scale 500 µm). G–I) Anvil used to crack nuts (O#71): general view (G); area of grain microfractured caused by superposed impacts (H; 20×, scale = 2 mm); central area with possible tribochemical alteration along the area where nuts were placed (I; 25×, scale = 2 mm).

Figure 11. Experimental hammerstones. A–D) Tool O#211 used on free-hand knapping and to split flakes, with details of the depression and battered area associated with a fracture scar (A; arrow indicates direction of the extraction); U-shaped incision (B; 10×, scale = 3 mm); grain crushing (C; 80×, scale = 500 µm); linear trace (D; 50×, scale = 800 µm). E–I) Tool O#186 used to crack nuts: general view (E); close-up of battered area (F); impact point with a conical shape (G; 40×, scale = 1 mm); grain microfracturing in the battered area (H; 10×, scale = 3 mm); superficial crushing (I; 40×, scale = 1 mm).

Figure 12. Pitted stones from WK (A) and JK (B), bearing additional battered areas in lateral and distal ends, and associated fracture scars (arrows indicate direction of extractions).

Figure 13. A–D) Group of artifacts from JK: core (A), pitted stones (B), small subspheroids (C), and large cutting tools (LCTs; D). E–G) Two small bipolar cores (classified by Mary Leakey as subspheroids; E), alongside outils écaillés (F) and experimental split flakes (G).

Figure 1

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Figure 13

Table 1

Summary of the experiments used as reference collection.

Experiment ID	Type of experiment	Anvil ID	Hammer ID	Items processed	Time (in minutes)	Total strikes
Exp. 30	Bipolar knapping	O69	O124	1 core	11	108
Exp. 31	Nut cracking	O71	O186	318 nuts (2.2 kg)	98	1211
Exp. 32	Freehand knapping and flake splitting	O246	O211	1 core and 8 flakes	17	F-H K: 48 FS: 147

Abbreviations: F-H K = freehand knapping; FS = flake splitting.

Table 2

Descriptive statistics of the archaeological pitted stones and the experimental reference collection.

	Length (mm)	Width (mm)	Thickness (mm)	Weight (g)	Volume ^a (cm ³)	Surface ^a (cm ²)	Density ^a (g/cm ³)	SA:V (cm ⁻¹)
Archaeological tools (<i>n</i> = 29)								
Minimum	61	42	30	112.9	50.5	71.6	0.78	0.804
Maximum	122	98	69	765.8	348.5	294.1	2.62	1.625
Mean	84.90	67.59	45.24	356.32	166.63	163.43	2.25	1.07
Standard deviation	14.13	12.75	10.10	174.75	86.95	59.30	0.40	0.20
Median	80	66	45	337	145.15	150.25	2.33	1.0465
Quartile 1	77	59	36.5	223.75	109.025	120.05	2.1775	0.909
Quartile 3	91.5	77	54.5	451.45	218.975	211.575	2.515	1.1695
Experimental tools (<i>n</i> = 6)								
Minimum	85	72	30	311.5	138.5	158.1	2.25	0.646
Maximum	146	113	70	1537	616.6	398.3	2.69	1.141
Mean	118.2	88.3	50.5	764.9	303.9	245.8	2.5	0.9

Standard deviation	21.9	17.6	13.1	437.9	174.3	91.6	0.1	0.2
Median	123.5	80.5	50.5	691.15	270.7	231.9	2.525	0.872
Quartile 1	97	75	42	406.525	163.1225	160.575	2.4075	0.7705
Quartile 3	134	109.25	59.5	1074.475	420.625	319.325	2.615	0.99175

Abbreviations: SA:V = surface-area-to-volume ratio.

^a Volume, surface area and density were computed from the 3D models in 24 archaeological tools.

Table 3

Descriptive statistics of results obtained from a GIS analysis of depressions.

	D area	D perimeter	D length	D width	DAC-DC	PA
Minimum	0.81	3.23	1.09	0.89	0.11	1.38
Maximum	17.23	17.5	6.49	4.58	1.6	36.25
Mean	4.90	8.55	2.90	2.11	0.60	10.41
Standard deviation	3.61	3.21	1.16	0.74	0.38	7.09
Median	3.59	7.98	2.64	1.95	0.53	8.00
Quartile 1	2.51	6.41	2.07	1.64	0.27	6.23
Quartile 3	5.84	10.22	3.45	2.44	0.83	13.11
Skewness	1.768	0.884	1.063	1.122	0.880	1.731
Kurtosis	3.328	0.609	0.814	2.069	0.159	3.341
Geom. mean	3.920	7.994	2.696	1.989	0.476	8.534
Coeff. var	73.542	37.583	39.891	35.045	64.474	68.091

Abbreviations: D = depression; DAC-DC = distance between the center of the tool and the centre of the depression. PA = percentage of the tool surface covered by the depression.

Table 4

Pearson correlation test comparing depression area, perimeter and the percentage of the tool surface covered by the depression (PA) against the slope.^a

		Minimum slope	Maximum slope	Mean slope
Area	Pearson correlation	0.333	0.146	0.224
	<i>p</i> (2-tailed)	0.067	0.433	0.226
	<i>n</i>	31	31	31
Perimeter	Pearson correlation	0.366*	0.285	0.391*
	<i>p</i> (2-tailed)	0.043	0.121	0.029
	<i>n</i>	31	31	31
PA	Pearson correlation	0.343	0.076	0.251
	<i>p</i> (2-tailed)	0.059	0.685	0.173
	<i>n</i>	31	31	31

^a Correlation is significant at the 0.05 level (2-tailed).

Table 5

Use-wear marks identified in the experimental materials.

Experiment ID	Type of experiment	Tool Id	Function	Linear Traces			Polish	Pits		Leveling	Micro-fractures		An
				Presence	Distribution	Density	Presence	Presence	Distribution	Presence	Presence	Type	
Exp 30	Bipolar knapping	O69	Anvil	No			No	No		No	Yes	Irregular	
Exp 30	Bipolar knapping	O124	Hammer	Yes	Clustered	Low	No	No		Yes	Yes	Irregular	
Exp 31	Nut-cracking	O71	Anvil	No			No	No		No	Yes	Irregular	
Exp 31	Nut-cracking	O186	Hammer	No			No	No		No	Yes	Irregular	
Exp 32	Freehand knapping and flake split	O246	Anvil	No			No	No		Yes	Yes	Irregular	
Exp 32	Freehand knapping and flake split	O211	Hammer	Yes	Scattered	Low	No	Yes	Scattered	Yes	Yes	Irregular	

Table 6

Early Stone Age sites where pitted stones have been reported.

Site	Archaeological area	Age (Ma)	<i>n</i> pitted stones	<i>n</i> punches/outils écaillés ^a	Reference
PDK Trenches I-III	Olduvai Gorge	0.8-0.6	14	23	Leakey and Roe, 1994
WK East C	Olduvai Gorge	0.8-0.6	15	39	Leakey and Roe, 1994
WK East A	Olduvai Gorge	0.8-0.6	68	130	Leakey and Roe, 1994
Gesher Benot Ya'aqov	Gesher Benot Ya'aqov	0.78	54	0	Goren-Inbar et al., 2002
WK Upper Channel	Olduvai Gorge	0.8-0.6	107	33	Leakey and Roe, 1994
HEB West Level 2b	Olduvai Gorge	0.8-0.6	4	5	Leakey and Roe, 1994
HEB West Level 2a	Olduvai Gorge	0.8-0.6	3	3	Leakey and Roe, 1994
HEB Level 3	Olduvai Gorge	0.8-0.6	3	1	Leakey and Roe, 1994
HEB East	Olduvai Gorge	0.8-0.6	3	4	Leakey and Roe, 1994
PDK Trench IV	Olduvai Gorge	0.8-0.6	2	1	Leakey and Roe, 1994
JK ferruginous sand	Olduvai Gorge	1.2-0.83	11	3	Leakey and Roe, 1994
JK grey sand	Olduvai Gorge	1.2-0.83	2	7	Leakey and Roe, 1994
TK Lower Floor	Olduvai Gorge	1.3	5	No data	Santonja et al., 2014

EF-HR	Olduvai Gorge	1.5-1.4	2	15	Arroyo and de la Torre, 2018
HWK EE	Olduvai Gorge	1.7-1.6	19	189	Arroyo and de la Torre, 2018
Gombore I	Melka Kunture	1.7-1.6	60	0	Chavaillon, 2004
Naiyena Engol 2	West Turkana	1.8-1.7	2	6 ^b	Roche et al., 2018

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^a We have included in this category those objects classified by the original authors as punches, outils écaillés, cores with écaillés, flakes/flake fragments with écaillés and angular fragments with écaillés.

^b Objects classified as bipolar flaked artifacts.