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RESEARCH

Qualitative and Quantitative Use-Wear Analysis of Percussive Stone Tools from Nyayanga (Homa Peninsula, Kenya)

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Abstract

This study presents a comprehensive examination of the function of 26 percussive stone tools (PSTs) from Nyayanga, an Oldowan site located on the Homa Peninsula in southwestern Kenya. These artifacts, dating between 3.032 to 2.581 million years ago, were found together with hominin remains and animal fossils with stone tool butchery damage. To determine the function of the PSTs, we adopted a multiscale approach that combines qualitative use-wear analysis using microscopic techniques at low and high power approaches with quantitative analysis, employing 3D surface models generated with profilometry. These analyses indicate that Nyayanga hominins used PSTs to access both plant (e.g., USOs) and animal (bone marrow) nutrients. The inferred multifunctionality of these tools hints at diverse dietary strategies and contributes to our understanding of human technological evolution.

Keywords Use wear analysis · Profilometry · Percussive stone tools · Oldowan technology · Dietary strategies

Introduction

Percussive stone tools (PSTs) were fundamental in lithic technology during the Lower Palaeolithic/Early Stone Age (ESA), primarily employed for striking cores and detaching flakes through techniques such as hard hammer percussion and bipolar reduction (Yeşilova et al., 2024). While their function in knapping is well documented, their potential role in food processing remains underexplored in Oldowan assemblages. Indeed, evidence suggests that PSTs were also used to fragment organic materials into smaller components (Adams, 2002; Harmand & Arroyo, 2023), leaving characteristic percussive damage on their surfaces (Haslam et al.,

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2013; Proffitt et al., 2021). This damage results from the forceful impact of a hand-held tool, propelled by muscular force, against another tool or material processed (Marchant & McGrew, 2005). Investigating this broader functional variability is important for reconstructing early hominin subsistence strategies.

The use of PSTs has been documented in some of the earliest lithic assemblages found in Late Pliocene and Early Pleistocene sites of East Africa, including Lokalalei 2C (2.34 Mya), the Olduvai Gorge Beds I and II (> 1.8 Mya), and Kokiselei 1 (1.79 Mya) and 4 (1.76 Mya) (Arroyo & de la Torre, 2016; Arroyo et al., 2020; Diez-Martín et al., 2010; Mora & de la Torre, 2005).

Use-wear analysis combining low and high-power approaches (Arroyo & de la Torre, 2018) has allowed scholars to attribute the wear on archaeological PSTs to a variety of activities, including bone breakage for marrow extraction (Arroyo & de la Torre, 2016; Arroyo et al., 2020; Assaf et al., 2020), the processing of plant tissue such as nuts (Arroyo & de la Torre, 2016; Goren-Inbar et al., 2002, 2015), meat processing (Mora & de la Torre, 2005), or the use of PSTs as hammerstones for knapping (Mora & de la Torre, 2005). These interpretations are supported by controlled experimental tests indicating that the characteristics of wear formation reflect factors such as raw material type, the material being processed, and the gestures being used (Calandra et al., 2020; de la Torre et al., 2013; Gilabert et al., 2012; Kononenko et al., 2021; Paixão et al., 2021; Sánchez Yustos et al., 2015).

Percussive technology may have been the precursor to flaking technology (De Beaune, 2004; Sanchez-Yustos et al., 2015). Accidental flake production during percussive activities has been documented in several non-human primate species, including chimpanzees, macaques, and capuchin monkeys, particularly in the context of nut-cracking (Bril et al., 2012; Haslam et al., 2009; Luncz et al., 2022; Marchant & McGrew, 2005; Proffitt et al., 2023, 2025). Since direct observations regarding percussive activities in extinct hominins are not possible, the investigation into percussive behavior among contemporary non-human primates has progressively become a useful avenue for interpreting the archaeological record (Proffitt et al., 2018), and has provided useful comparative data for the evolution of hominin technology and landscape use (Haslam et al., 2013, 2016). Primate archaeology is focusing its field of research by analyzing non-human primate percussive stone tool use in a variety of food-processing activities. These activities include cracking nuts, fruits, and processing shellfish (Arroyo et al., 2021; De Moraes et al., 2014; Falòtico et al., 2019; Haslam et al., 2016; Proffitt et al., 2016, 2018; Sirianni et al., 2024; Visalberghi et al., 2013). Moreover, capuchin monkeys also dig using stone tools to reach carbohydrate-rich underground storage organs (USOs) (Falótico et al., 2017).

To further investigate PST function, we conducted a combined qualitative and quantitative analysis of 26 well-preserved PSTs from Nyayanga, a Late Pliocene Oldowan locality (Plummer et al., 2023). The exceptional preservation of these tools provided an ideal opportunity for macro- and micro-use-wear analysis, supported by a dedicated reference collection. Additionally, we conducted a preliminary test to assess the potential of quantitative analysis in the study of use-wear patterns. In this regard, confocal microscopy (Delgado-Raack et al., 2022; Paixão et al., 2021b), morphometric GIS analysis, and spatial patterning analyses performed using a 3D scanner (Benito-Calvo et al., 2015; Caruana et al., 2014) or photogrammetry

(Delgado-Raack et al., 2022; Marulli et al., 2023; Proffitt et al., 2021; Sorrentino et al., 2023; Zupancich & Cristiani, 2020) are the most commonly employed methods. In this study, non-contact 3D optical profilometry was selected over those methods because it has a large (cm-sized) area of analysis while maintaining high vertical resolution (few nm) and accuracy, and removes the need for image stitching, application of computational algorithms, and standardization of the hardware components (e.g., light source, objectives, etc.).

The main objective of this study is to clarify the functional role of the percussive stone tools from Nyayanga. Through an integrated use-wear and 3D analysis, and considering the possible effects of the post-depositional alterations, we define how these tools were used and for which specific tasks. The working hypothesis is that they were employed in diverse percussive activities, leaving diagnostic wear patterns that can be linked to specific materials and actions.

The aim of this study is to refine interpretations of early hominin tool use between 3.032 and 2.581 million years ago in Africa. We provide consistent evidence for the functional diversity of PSTs, reinforcing their important role in food-processing activities. In addition, this study highlights the value of high-resolution qualitative and quantitative integrated methods in wear analysis.

The Nyayanga Locality

Nyayanga is situated on the western shoreline of the Homa Peninsula in southwestern Kenya,on the Winam Gulf of Lake Victoria (Fig. 1). (U-Th)/He dating of apatite crystals, magnetostratigraphy, and biostratigraphy indicate that Bed NY-1 was deposited early in the C2an.1n Subchron (3.032—2.581 Ma) (Plummer et al., 2023), making Nyayanga one of the oldest, if not the oldest, Oldowan localities discovered to date. Over 1,776 fossils and 330 artifacts including the PST sample analyzed here were recovered from the top half of NY-1. These include several hippo bones that display damages related to carcass processing, a *Paranthropus* sp. tooth, and chipped stone tools displaying butchery-related and plant processing use-wear (Plummer et al., 2023). The upper NY-1 deposits consist largely of clayey silts with rare sandy granules and pebble lenses deposited as overbank deposits from a westward flowing paleochannel that was situated roughly 40 m away from the excavations. Stable carbon isotopic analysis of pedogenic carbonates, dietary reconstruction using tooth enamel isotopes, and bovid taxonomic frequencies indicate that hominin activities took place in a wooded grassland to grassy woodland, bushland, or shrubland along the ancient channel within a mesic savanna biome characterized by an abundance of C_4 grasses and herbaceous plants. A freshwater spring provided an additional attractive resource at the locality. The hominin (*Paranthropus* sp.) molars (one from the surface of NY-1 and one in situ at a hippo butchery site, excavation 3) have stable carbon isotope values demonstrating a heavy reliance on C_4 foods. The lithic assemblage is distinct in having a high frequency of cores (20.6%, n = 68), and a high frequency of artifacts evincing percussion activities (7.0%). The landscape-scale distribution of raw material sources around Nyayanga suggests that many of these durable stone tools were procured from over 10 km away (Finestone

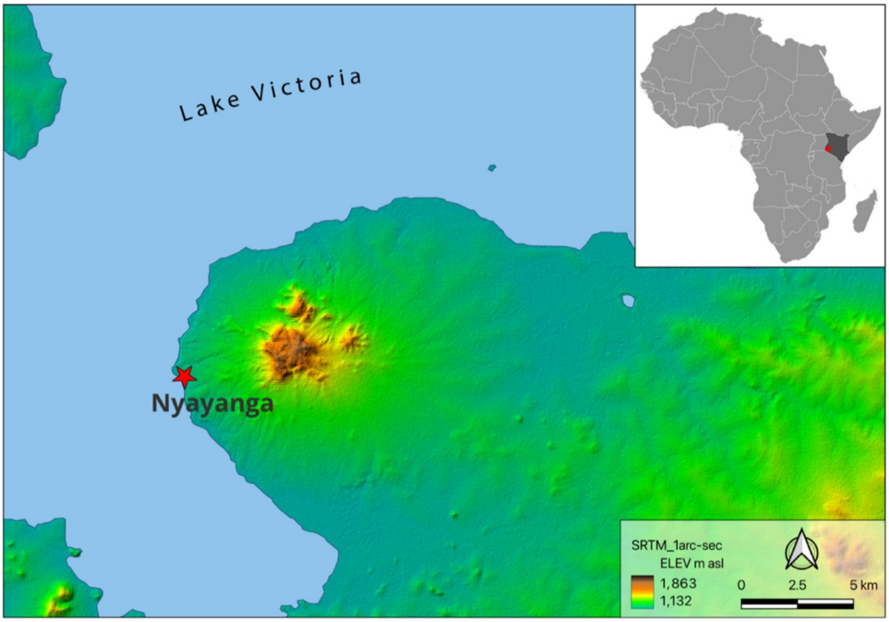

Fig. 1 The geographic location of Nyayanga (Kenya) on the western margin of the Homa Peninsula on the Winam Gulf of Lake Victoria. The elevation model is processed using ArcGIS software

et al., 2025). The tools and technology employed by Nyayanga's hominins are otherwise comparable to other Oldowan assemblages and provide evidence of on-site flake production through hard hammer percussion (Plummer et al., 2023).

Materials and Methods

Materials

Nyayanga artefacts were analyzed in 2019 at the National Museums of Kenya (NMK) in Nairobi. Initially, we examined 50 stone objects in the collection, consisting of unmodified cobbles and cores. Microscopic analysis was used to detect wear-related traces to determine whether the objects were percussive stone tools. Of the 50 stones, 26 showed interpretable wear traces, while 6 items displayed significant alterations (e.g., high gloss, diffuse crystal abrasions) that precluded definitive categorization within a functional class, and 18 showed no signs of wear. The assemblage includes quartz ($n=4$), quartzite ($n=14$), rhyolite ($n=2$), granite ($n=3$), red felsite ($n=1$), phonolite ($n=1$), and unknown ($n=1$) raw materials (Plummer et al., 2023) (SI, Table 1). The PSTs can be categorized into two technological groups: pounded pieces (PP, e.g., unmodified cobbles used as hammerstones and/or to pound food and other materials; $n=7$), and flaked pieces (FP, i.e., cores; $n=19$) (Fig. 2) (Plummer et al., 2023).

Out of the 26 PSTs analyzed for pounding damage, 11 (42%) displayed well-preserved surfaces that have not been altered by diagenetic processes. However, some alterations or a combination of them, identified using different microscopic magnifications, were observed on other specimens in the sample. Six items (23%) exhibited a gloss appearance under the stereomicroscope that did not affect the preservation of the macro- and micro-traces. Two tools (8%) exhibited a combination of gloss appearance and pitting, with the latter being visible under the metallographic microscope. Two samples (8%) showed crystal abrasions and one tool (4%) a combination of crystal abrasion and pitting. Four tools (15%) displayed slight pitting on single crystals (**SI,** Fig.a1). Five specimens (19%) had adhering concretions, although none were present on the functional areas.

Methods

Use-Wear Analysis

Use-wear analysis was performed on archaeological and experimental PSTs at the Laboratory of Technological and Functional Analyses of Prehistoric Artefacts (LTFAPA), Sapienza University of Rome. In tribology (Society of Tribologists and Lubrication Engineers, n.d.) wear is a progressive modification of a surface caused by repeated contact and relative motion with another surface. This approach allows for the assessment of material properties influencing wear formation (e.g., hardness, grain size and chemical composition of raw material and motion), distinguishing use-related wear patterns from post-depositional alterations (Adams et al., 2009; Cnuts & Rots, 2024; Teer & Arnell, 1975).

Fig. 2 Examples of percussive stone tools from Nyayanga. Flaked pieces (**1.** NY15-33; **3.** NY15-135; **5.** NY15-111; **6.** Exc5-16; **7.** NY12-58; **9.** NY18-12; **10.** NY17-8) and pounded pieces (**2.** Exc3-103; **4.** Exc3 −37; **8.** Exc3-485; **11.** NY18-15)

In this study, a RH-2000 Hirox digital microscope with magnifications up to 2000X was used for the analysis of macro-traces, a Nikon Eclipse metallographic microscope equipped with reflected light with a range of magnifications from 50 to 500X for identification of micro-traces, and a Hitachi Tabletop TM3000 scanning electron microscope (SEM), in complete vacuum mode, with magnifications up to 5000X and accelerating voltage 15 kV for the micro-wear analysis. The NMK does not allow the export of archaeological artifacts, so observations of micro-traces were made on gold-coated epoxy resin casts (i.e., Araldite® LY 554 and HY 956) from silicon molds (Provil Novo Light Fast Heraeus®) of functional areas identified using a Nikon SMZ stereomicroscope in Nairobi.

Well-preserved use-wear marks were observed on 26 Percussion Stone Tools (PSTs) from Nyayanga (Homa Peninsula, Kenya). To ensure a reliable interpretation of these traces, we combined low and high-power approaches as suggested by previous studies (Bello-Alonso et al., 2019; Ollé et al., 2016; Pedergnana et al., 2017; Knutsson, 1988; 2015). We identified areas on the tool's surface with preserved macro-wear (i.e., flake removals, macro-pits) highlighting active areas on the stone artefacts, and then examined the same area with the metallographic microscope and SEM to observe microwear (i.e., polish, micro-pits, cracks on quartz grains, and striae). Indeed, the SEM provides a more precise view of textural features by removing the glare that arises from the rock's optical properties (Ollé et al., 2016). High magnification enabled us to identify micro-wear and specific post-depositional phenomena present on the crystal surface (e.g., abrasions, striations and pitting) (Werner, 2018). Use-wear marks on quartz and quartzite are commonly observed on the surface of a single quartz crystal or small clusters of crystals, as well as on small patches of silica matrix in quartzite (Lemorini et al., 2014). Combining different magnifications was necessary to reach an accurate use-wear interpretation. On raw materials such as quartzite, quartz, and rhyolite, the correlation between macroscopic and microscopic use-wear is not always direct. Macroscopically visible battering areas—typically involving crushing or localized depressions—are useful for identifying zones of intensive use but cannot alone determine the worked material.

Traces were analyzed and described following standard protocols. Macroscopic traces (negatives of scars/flake removals, macro-pits and macro-striations) were described (Arroyo & de la Torre, 2016, 2018; Arroyo et al., 2021; de la Torre et al., 2013). For the examination of micro-traces (including polish texture, topography, extension, micro-striations, micro-pits, levelling, crystal breakage and abrasions, see detailed parameter descriptions in Table 1, SI_1), we referred to studies employing high-power analytical methods (metallographic microscope and SEM) on quartz, quartzite, and rhyolite raw materials, including analyses on chipped and groundstone tools (Bello-Alonso et al., 2019; Berruti & Cura, 2016; Caricola et al., 2018, 2020; Clemente Conte et al., 2015; Dubreuil et al., 2015; Fernández-Marchena & Ollé, 2016; Gibaja et al., 2009; Hayes et al., 2018; Knutsson et al., 2015; Lemorini et al., 2014, 2019; Ollé et al., 2016; Pedergnana and Olle, 2017; Pedergnana et al., 2017; 2020a, 2020b; 2020a, 2020b; Taipale, 2012; Taipale & Rots, 2019; van Gijn, 2010; Venditti et al., 2016; Werner, 2018).

Table 1 Detail of use-wear observed on PSTs experimental replicas

ID	Experiment	PST Raw Material	Time of Use	Macro Traces	Micro Traces								Type of anvil associate
					Polish			Leveling	Abrasion	Linear Features/ striae	Micro-Pits	Cracks	
					Texture	Topography	Extension						
2	***Manihot esculenta*** (cassava)	Rhyolite	4 h	Detachment of micro-flakes associated with irregular pits	Smooth	Domed + Cratered and pitted	On the top of the crystals and rough on the bottom	Yes	None	Narrow	None	On quartz grains	Soft soil, on the ground surface
7	***Corylus*** (hazel tree)	Quartz	4 h	Slight rounding of the grains	Rough	Domed	Along the ridges of the crystals	None	Yes	Narrow, Tapered, Short, Parallel	None	None	Soft soil, on the ground surface
4	***Armoracia rusticana*** (horseradish)	Rhyolite	4 h	Overlapping, sub-circular pits	Rough	Domed + Pitted	On the top and bottom of the crystals	Yes	Yes	Narrow, Long	None	On quartz grains; quartz removals	Stone anvil
36	***Dioscorea* spp.** (yam)	Quartz	4 h	Cracks on the grains and micro-flakes	Smooth	Domed	On the top and bottom of crystals	Yes	Yes	Narrow, Short, Polished, + Chaotic	Sub-triangular and sub-circular pits	On quartz grains	Stone anvil
9	***Passiflora edulis*** (passion fruit)	Rhyolite	4 h	Slight rounding of the grains	Rough	Domed	On the top and edges of the crystals	None	None	None	None	None	Stone anvil
35	***Annona cherimoya*** (custard apple)	Rhyolite	4 h	Slight rounding of the grains	Rough	Domed	On the top and edges of the crystals	None	None	None	None	None	Stone anvil
5	***Ovis aries*** (sheep femora, ribs with attached flesh and tendons)	Rhyolite	4 h	Detachment of 1 Macro-flake; cracks on the grains	Smooth	Flat	On the top of the crystals	Yes	Yes	Furrows, Long, Deep, Parallel, Polished	None	On quartz grains	Stone anvil

Experimental Trials

Experimental replicas of percussive stone tools made of both quartz and rhyolite were used to crush plant and animal materials, using a thrusting percussion gesture, for over four hours (Table 1; SI, Fig. 2). Additionally, we used an extensive reference collection of quartzite samples available at the LTFAPA (Sapienza University, Rome, Italy) to further study the formation of traces (Lemorini et al., 2014). We collected the same raw materials used by hominins at Nyayanga from conglomerates around the Homa Peninsula (Kenya) and transported them to the LTFAPA. Therefore, we selected raw materials, e.g., rhyolite, which at Nyayanga contains smaller quartz grains than quartzite, interspersed with more compact quartz. The formation of wear traces on both the crystals is highly comparable to that observed on quartz and quartzite in the LTFAPA experimental reference collection (Lemorini et al., 2014). All replicas were thoroughly documented prior to use, including the creation of silicone and epoxy resin casts (see Section "Use-Wear Analysis").

Percussive stone tools replicas were used to process food items with different physical properties, including soft and juicy, such as passion fruit (*Passiflora edulis*) and custard apple (*Annona cherimoya*); pulpy and fibrous like cassava (*Manihot esculenta*), and woody and fibrous such as horseradish (*Armoracia rusticana*). To process underground storage organs (USOs), a crushing action was used, with larger tubers and roots over 50 cm in length being initially struck to break them open before being crushed. The wood reference collection was created by pounding bark from hazel (*Corylus*) tree branches. Bone processing reference specimens were created by fracturing defleshed fresh sheep (*Ovis aries*) femora and ribs. Additionally, we conducted experiments on bones with flesh and tendons still attached.

In the experimental trials, active tools were used against two types of passive surfaces: flat stone anvils and soft soil. These support surfaces were included to reflect a range of potential use conditions, although the specific types of passive elements used at Nyayanga are currently unknown. The type of surface used in each trial is indicated in Table 1.

Profilometry

A Nanovea Jr25 portable non-contact 3D optical profilometer was used to determine the surface morphometrics of the functional areas of a selection of twenty epoxy replicas of the archaeological ($n=14$; samples were selected based on similar raw material texture to minimize variables) and experimental samples ($n=6$). For each replica, the morphometric mapping was performed on a single area as large as possible, up to 25×20 mm, thus covering most of the sample surface; for selected materials, the analyses were conducted in two different areas to explore the effects of different levels of use and post-depositional alteration. The profilometer is equipped with a set of three optical pens providing a vertical resolution (height repeatability) of 3.4, 17.0, and 31.0 nm within a measurement range of 1.1, 3.0, and 10.0 mm, respectively. A lateral resolution (step size) of 30 μm and a scan speed of 1.42 mm/s (dual-frequency acquisition of 100–1800 Hz) were used. The 3D maps were processed with the Gwyddion v2.60 (Czech Metrology Institute) software by a four-step procedure:

Form removal: the background was removed setting a second-degree polynomial.
Outlier masking: the surface anomalies of the bubbles formed during the replica preparation and any other topographic outlier were identified by a mixed automated and manual masking, treated by Laplace's interpolation, and excluded from the final numerical dataset.
Microroughness filtering: a conservative denoise filter and then a Gaussian smoothing filter were applied for correcting minor artifacts.
Frequency split: the high-pass roughness surface (short wavelength) and the low-pass waviness surface (long wavelength) were separated and extracted applying a wavelength cut-off (nesting index) of 1 mm (with a 0.02 edge width and Laplace boundary treatment), chosen after preliminary tests and according to the standard EN ISO 25178-3 (2012).

The final calculation of the texture parameters, including those from the standards EN ISO 25178–2 (2022) and EN ISO 4287 (1998), was performed by a combined 3D and 2D analysis, i.e., processing both the height map and up to four height profiles traced on it with different orientations. For each sample, two datasets were collected on the total mapped area and on one smaller Sect. (2×2 mm) where the concentration of use-wear traces was the highest, as observed under the microscope. The calculations were done both before and after the frequency split; therefore, taking into account both the combination of the roughness and waviness surfaces and only the high-pass roughness surface. This distinction was deemed necessary because standardized processing methods of 3D maps acquired by profilometry or confocal microscopy on archaeological materials do not exist (Borel et al., 2021; Calandra et al., 2019; Pedergnana et al., 2020a, 2020b; Stemp, 2001), and different choices of the filtering parameters (e.g., the cut-off value) may greatly affect the morphometric analysis (Fig. 3). This applies to all studies of archaeological finds or cultural heritage materials (e.g., Germinario et al., 2022).

The calculations involved an array of morphometric parameters, including root mean square (RMS) roughness, mean roughness, skewness, kurtosis, maximum peak height, and maximum valley depth. For this study, the 2×2 mm areas with combined waviness and roughness surfaces were chosen as reference, thus excluding the processing step of frequency split. This choice was motivated by the large data discrepancy comparing the different calculation approaches: processing the high-pass surfaces only would flatten texture particularities, whereas analyzing the total mapped areas would yield high data scattering affected by the waviness component and random topographic irregularities masking the micro traces. The relevant dataset was statistically processed by a principal component analysis (PCA) (performed with Statgraphics Centurion 19 based on the correlation matrix), which allows for recognizing possible multivariate trends of the textural parameters linked to how the PSTs studied were used; in this regard, the PCA interpretation was guided by the functional attributions from the previous qualitative analyses and allowed further validating the relevant findings. From the whole morphometric dataset, six variables

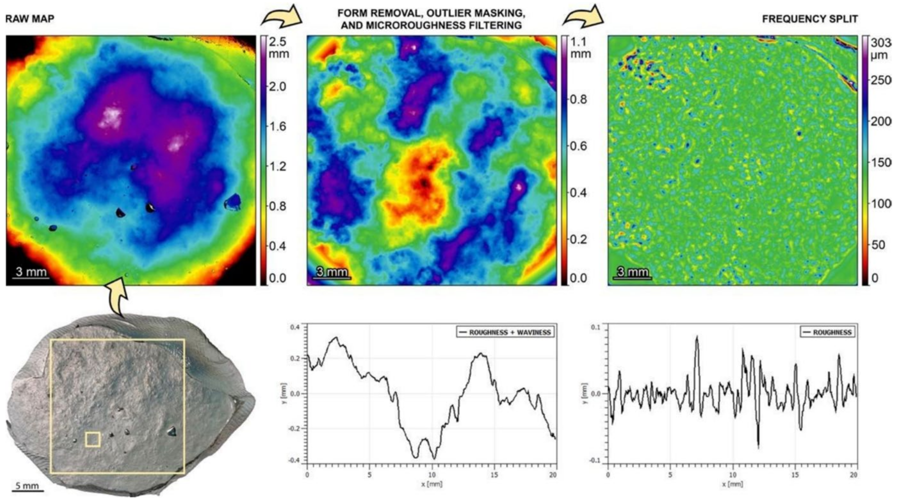

Fig. 3 Morphometric analysis of an archaeological replica, with the indication of the 20×20 mm area scanned and the sub-selection of a 2×2 mm area richest in use-wear traces; the arrows follow the map processing workflow described in the text, while the plots display the topographic trend measured along the same horizontal profile in the middle of the map before and after the frequency-split step

(Sq, Sp, Sv, Sz, Rvm, and Rpm) were selected for the PCA. The choice was guided by the need to simplify data interpretation, rule out variables being too similar to each other (e.g., RMS and mean roughness) or showing irrelevant variability (e.g., skewness and kurtosis), and combine the results of both the 2D and 3D analyses.

Results

Use-Wear on Experimental Reference Collection

Although used for 4 h, macroscopic examination of the experimental tools revealed only a few traces. Using a stereomicroscope (10x-80x), however, we observed pits and cracks localized on the pounding area. Flake detachments occurred only during the bone pounding experiments. The most prominent traces, usable for distinguishing materials processed and actions carried out, were identified through high-magnification examination. We employed the metallographic microscope (with a magnification range of 50x-500x) to isolate specific areas where the microtraces showed excellent development. Our findings were further supported by observing and documenting the same area using the Scanning Electron Microscope (up to 5000x).

The microwear patterns observed included polishes, micro-pits, abrasions, and cracks. Furthermore, linear friction features i.e., sleeks (narrow and fine striations) and furrows (large and deep tapering striations) (Fullagar et al., 2006; Knutsson et al., 1988; Ollé et al., 2016; Pedergnana & Ollé, 2020) were observed. Processing of roots such as cassava and yams resulted in a smooth, flat polish with irregular pits and striations; while hazel wood bark processing produced a rough, domed polish with short, parallel, and tapering micro-striations. Horseradish processing created a polish with well-defined, round micro-pits and unpolished long narrow striations. Bone yielded a distinctive polish with deep crystals leveling and furrow striae polished associated. The handling of soft, juicy fruits resulted in a rough and domed polish on the crystal edges with no leveled topography (**see** Table 1; SI, Figs. 3, 4, 5, 6, 7, and 8).

Use-Wear on Archaeological Tools

Our use-wear analysis of the 26 PSTs from Nyayanga reveals that they were used intensively to crush/fragment both plant and animal tissue (Table 2). Specifically, we were able to identify use-wear from processing: (1) woody plants/woody USOs ($n=7$ artefacts); (2) pulpy USOs ($n=7$ artefacts); (3) mix of plant materials ($n=3$ artefacts); (4) bone and animal soft tissue (e.g., muscle) ($n=4$ artefacts). On five items, significant diagenetic alteration (i.e., abrasion of the crystals) hindered our ability to define their specific use. Despite lacking clear micro-wear evidence, the presence of macro-traces observable at 10x, such as macro-pits indicative of battering, suggests that these tools can be classified as PSTs. Microscopic analysis is therefore essential to infer function, as it allows for the identification of diagnostic features such as polish texture, microtopography, striation morphology, and crystal-level damage. These attributes provide important data on the nature and consistency of the processed materials (e.g., plant vs. animal tissue; soft material vs. hard material), as well as on the gestures and techniques involved in percussive activities (e.g., thrusting percussion) (De Beaune, 2004). In this study, macroscopic observations guided our sampling strategy, while functional interpretations relied on detailed microscopic analysis. The traces related to the processing of woody plants/woody USOs (Fig. 4) exhibit rough/domed pitted polish in five samples. The polish extended on the top and bottom of the crystals. They may present long narrow and tapering striations, as well as pits and cracks on the crystals, which also appear rounded. These traces share similar characteristics with experimental replicas related to the processing of a USO (*Armoracia rusticana*) that presents starch grains but also has a woody texture with a high fiber content.

The traces interpreted as resulting from the processing of pulpy vegetal material (USOs) (Fig. 5) on six artefacts present a smooth/domed and cratered/pitted polish, with the trace being more developed on the top part of the crystals, but sometimes rough on the bottom (Adams, 1993). The crystals appear rounded, and narrow striae with the same orientation are present. Experimentally, the described traces seem to be compatible with use-wear produced by some tubers (USOs), e.g., *Manihot esculenta*, which is distinguished by a stiff white flesh with high starch grain content.

In three cases, the function of the PSTs has been linked to the processing of multiple plant types (Fig. 6), perhaps several different USOs with different consistencies. In these cases, the traces appear highly developed, evidently connected to intense use, with the crystals almost amalgamated. The polish appears rough to smooth/domed. When the crystals are distinguishable, they appear rounded, with cracks and striae, and have polish extending to their top or bottom.

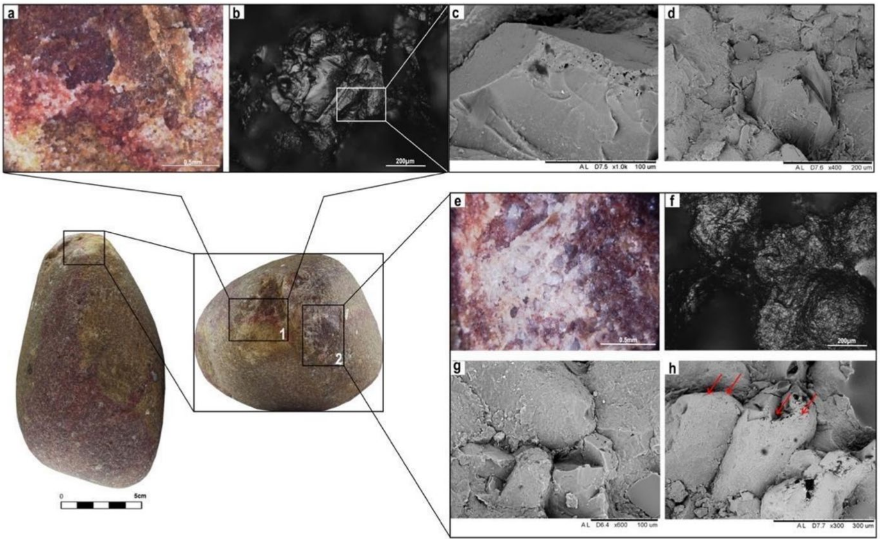

Fig. 4 Percussive stone tools in quartzite from Nyayanga (field number Exc3-485). The use-wear is indicative of the processing of plant materials with woody consistencies. In detail, Area 1: (**a**) concentration of macro-pits and flake removals; (**b**) rough and domed micro-polish observed under the metallographic microscope; (**c-d**) the same area observed using the SEM reveals the presence of cracks and leveling on the top of the angular crystals where the polish develops. Area 2: (**e**) rounded crystals; (**f-g**) rough and domed polish developed on the top, bottom, and into the intergranular space; (**h**) narrow-tapering parallel linear features

Four Nyayanga PSTs were used in percussion/fragmentation of bone (Figs. 7, 8). The polish associated with bone processing appears smooth and flat, developing on leveled grains, and is accompanied by deep furrow striae, diagnostic features of repeated impact on hard mineralized surfaces. In contrast, wear associated with muscle tissue processing appears rough-domed and more irregular in texture, a pattern experimentally linked to contact with softer organic materials. In two cases, the distribution and texture of the polish suggest the possibility of processing both bone and muscle tissue, as the observed wear exhibits characteristics of both contact types. These distinctions allow for a clear differentiation between bone percussion and soft tissue processing while acknowledging instances of overlapping use.

Linear friction features such as narrow and fine striae and large and deep tapering striations (furrows) were present on crystals in all analyzed archaeological artifacts. Linear friction features on crystals are found in the experimental sample on PSTs used for processing USOs and those used to process bone. However, they are absent on experiments used to process soft fruits (i.e., *Passiflora edulis* and *Annona cherimoya*). In both the experimental and archaeological PSTs, the striae connected to bone processing were found to be more distinctive, often appearing very deep, parallel, and large. In contrast, the striae connected to the processing of plant tissues are more delicate and finer (tapering striae are more frequent). Ollé and colleagues (2016) noted that morphological differences among linear friction features (i.e., striae) can be observed, but it is often challenging to establish a direct link

Table 2 Percussive stone tools from Nyayanga. Details of macro and micro traces observed under the stereomicroscope, metallographic microscope and SEM

N	Specimen #	Macro-Traces (Stereomicroscope)	Micro-Traces (Metallographic Microscope and SEM)	Use-Wear Interpretation	Intensity of use
1	Exc3-103	Flake removals; pits	Cracks on the crystals; rough to smooth/domed pitted polish; levelling; furrow striae; polish extension on the top and bottom of the crystals	Bone tissue + probably soft tissues	High
2	Exc5-16	Flake removals; pits	Cracks on the crystals; smooth/flat polish; narrow striae; polish extension on the top of the crystals	Pulpy vegetal materials (USOs)	High
3	NY18-12	Flake removals; pits	Smooth/flat, cratered polish; long narrow striae; polish extension on the top of the crystals	Pulpy vegetal materials (USOs)	Medium
4	Exc3-485	Flake removals; pits	Rough/domed polish on the top and bottom of the crystals; Cracks on the crystals; narrow and furrows parallel striations; abrasions	Woody plants/woody USOs	High
5	NY15-134	Flake removals; pits	Altered	Indeterminable	Low
6	NY16-92	Flake removals	Cracks on the crystals and furrows striae + alteration	Indeterminable	Low
7	Exc3-37	Pits	Cracks and pits on the crystals, smooth/flat pitted polish; polish extension on the top and bottom of the crystals	Pulpy vegetal materials USOs)	High
8	NY15-66	Pits and cracks on the high ridges	Altered	Indeterminable	Low
9	NY18-15	Flake removals; pits	Cracks on the crystals; micro-pits, levelling; rough to smooth polish; the polish extension on the top of the crystals, but the rough polish is also on the bottom; deep long parallel narrow striae	Bone + probably soft tissues	High
10	NY15-111	Pits on the high ridges	Rough/domed pitted polish, micro-pits, rounded crystals; furrows and narrow striations; the crystals are completely destroyed by the use (amalgamate crystals); polish extension on the top of the crystals	Mix vegetal materials	High
11	NY15-104	Flake removals; pits	Smooth/flat, cratered polish; micro-pits; narrow striae; polish extension on the top of the crystals	Pulpy vegetal materials (USOs)	Medium

Table 2 (continued)

N	Specimen #	Macro-Traces (Stereomicroscope)	Micro-Traces (Metallographic Microscope and SEM)	Use-Wear Interpretation	Intensity of use
12	NY16-52	Pits on the high ridges	Rough/domed pitted polish; pits and cracks on the crystals; long narrow striations; polish extension on the top and bottom of the crystals	Woody plants/woody USOs	Medium
13	NY12-79	Pits on the high ridges	Rough/domed polish; narrow striae; pits and cracks; polish extension on the top and bottom of the crystals; abrasions	Woody plants/woody USOs	Low
14	NY12-84	Pits on the high ridges	Rough/domed pitted polish, long narrow striae; polish extension on the top and bottom of the crystals	Woody plants/woody USOs	High
15	NY15-55	Pits on the high ridges	Rough to smooth/domed polish; levelling; long parallel furrows striae; levelling; polish extension on the top of the crystals	Bone tissue + probably soft tissues	Medium
16	Exc3-164	Flake removals; pits	Rough/domed polish; pits and cracks on the crystals; long parallel furrows and narrow striae; the polish extension on the high ridges of the crystals; abrasions	Woody plants/woody USOs	High
17	NY17-16	Sporadic pits on the high ridges	Altered	Indeterminable	Low
18	NY17-8	Pits on the high ridges	Smooth/flat polish, sporadic pits and narrow striae. The polish is rough into the intergranular space and smooth on the top of the crystals	Pulpy vegetal materials (USOs)	High
19	NY17-32	Probably pits on the high ridges	Altered	Indeterminable	Indeterminable
20	NY16-166	Pits on the high ridges	Rough to smooth/domed polish; narrow striae isolated/oriented; cracks and pits on the crystals; polish extension on the top and bottom of the crystals	Mix vegetal materials	High
21	NY12-58	Flake removals; sporadic pits	Rough to smooth/domed polish; pits and cracks on the crystals; sporadic narrow striae; polish extension on the top of the crystals	Mix vegetal materials	Low

Table 2 (continued)

N	Specimen #	Macro-Traces (Stereomicroscope)	Micro-Traces (Metallographic Microscope and SEM)	Use-Wear Interpretation	Intensity of use
22	NY15-33	Overlapping pits, which create a depression on the surface of use, associated with bundles of long striations having different orientations	Smooth and flat cratered/pitted polish; polish extends to the top and bottom of the crystals; pits and narrow oriented striae	Pulpy/oily vegetal materials	High
23	NY15-135	Flake removals; pits	Rough to Smooth/flat polish; furrows long, deep, parallel, polished striations; levelling; cracking of the grains; micro-pits; polish extends to the top of the crystals	Bone tissue	Medium
24	NY15-102	Pits on the high ridges	Rough to smooth/domed polish; pits, amalgamate crystals; polish extends to the top of the crystals, on the high ridges; narrow striae	Woody plants/woody USOs	High
25	NY16-168	Flake removals; pits (sporadic)	Rough to smooth/domed pitted polish; pits and cracks on the crystals; long narrow striations; polish extension on the top of the crystals; abrasions	Woody plants/woody USOs)	Low
26	Exc3-175	Pits	Leveling; Smooth and domed polish on the top of the grains	Pulpy vegetal materials (USOs)	Low

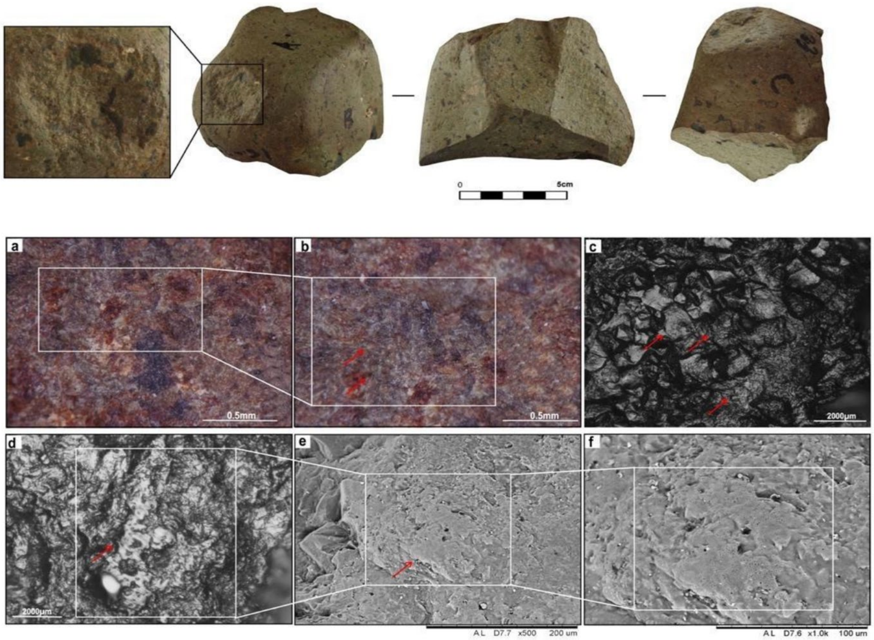

Fig. 5 Percussive stone tools in phonolite from Nyayanga (field number NY15-33). The use-wear is indicative of the processing of pulpy plant tissue. In the square, the functional area is characterized by: (**a-b**) a concentration of pits and a band of striae; (**c**) polish distributed on the top and bottom of the small crystals; (**d**) smooth, cratered, and pitted polish, more rough in the bottom part; (**e**) the polish observed under the SEM; (**f**) gentle narrow linear features on the polish

between these features and the worked materials. This is because striae are influenced by various tribo-system variables, including the physical characteristics of the elements involved (e.g., abrasive particles or the contact with another surface), the properties of the interfacial medium material, and the energy of the dynamic contact between surfaces. As a result, it can be difficult to draw definitive conclusions about the source materials of striae or linear features based solely on their morphology (Knutsson, 1988; Ollé and Vergès, 2008).

We observed a higher count of striae on our experimental samples compared to the Nyayanga archaeological artifacts. This discrepancy might be influenced by the type of percussion base employed in pounding. Specifically, we lack information regarding whether hominins worked on stone anvils or directly on the ground. In our experiments, stone anvils were employed, which could potentially account for the increased number of striae. The type of anvil or anvils, e.g., stone, the ground, or perhaps wood, used by Nyayanga hominins is unknown. More targeted experiments are necessary to better define differences in traces created using different types of anvils.

Finally, while the analysed tools exhibit wear patterns consistent with the processing of plant and animal materials, we do not exclude the possibility that some of these PSTs were originally used in a multifunctional manner—for example, for knapping or sequentially engaging with diverse materials. However, use-wear

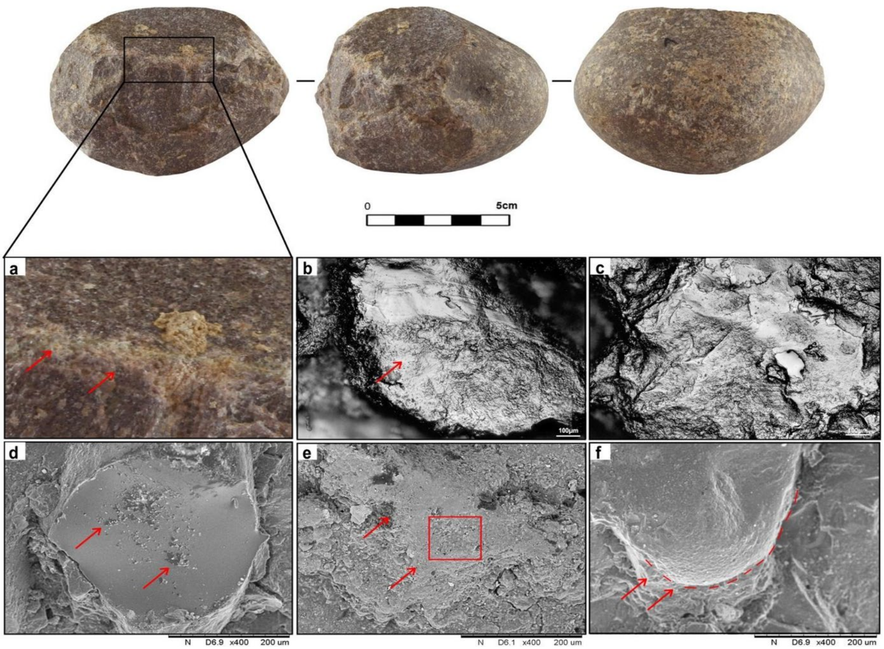

Fig. 6 Percussive stone tools in quartzite from Nyayanga (field number NY15-111). The use-wear is indicative of the processing of a mix of plant tissues. In detail, (**a**) pits on the active percussion area; (**b-c**) rough polish on the abraded crystals; (**d**) overlapped pits on the crystal and striae; (**e**) narrow linear features (indicated by the arrows) and pits (in the square), the entire area is completely modified by use, and the crystals are amalgamated; (**f**) rough polish on the top of the crystal (the lines delineate the crystal's outlines)

analysis primarily captures the most recent or most intense phase of use. Consequently, our functional interpretations reflect the final activities that left the most recognizable traces on the artefacts.

As a matter of fact, the macro- and especially micro-wear traces observed on the Nyayanga pounding tools differ markedly from those typically associated with flake production as testified by our reference collection at LTFAPA (that includes specimens used as knapping hammerstones). These traces appear as extensive flattened areas with deep, linear striations, often isolated (generated by the friction stone VS stone). Some PSTs could have been multifunctional, and flaking might have occurred earlier in their use-life. To date, no evidence of this kind has been documented at Nyayanga.

Use-Wear Quantification

The full morphometric dataset is attached as Supplementary Information_2. The score plots from the PCA performed for the archaeological samples and the experiments are shown in Fig. 9. The relevant data were processed separately, since only the surface features of the experimental materials derive comparable

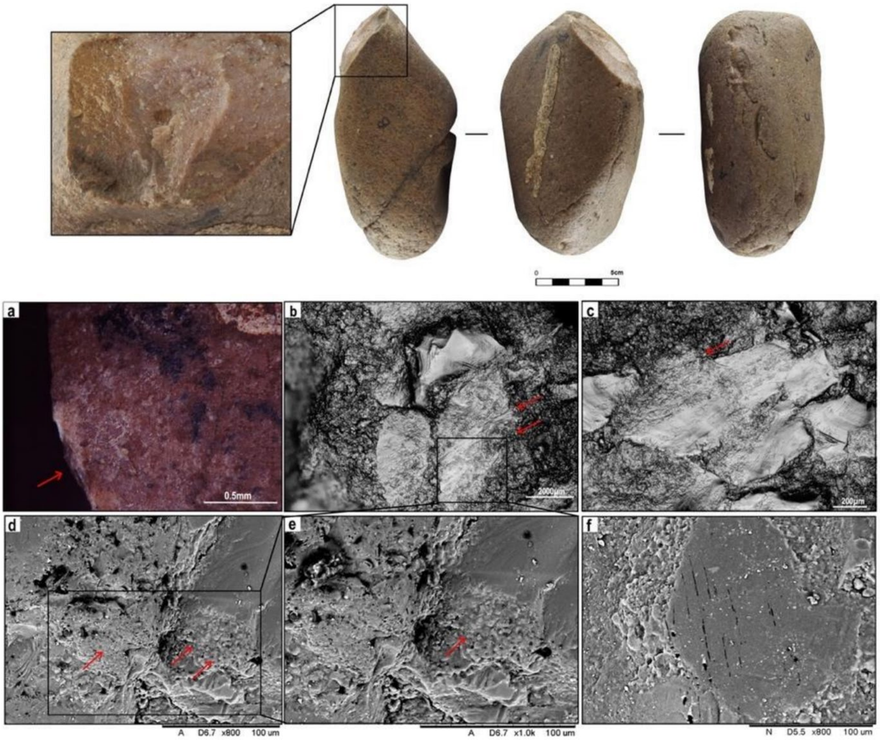

Fig. 7 Percussive stone tools in rhyolite from Nyayanga (field number NY15-135). The use-wear is indicative of the processing of bone tissues. In detail, (**a**) area that shows percussion marks; (**b-c**) rough to smooth-flat polish and leveled area; (**d-e**) the same area (b-c) observed under the SEM; (**f**) furrow parallel linear features

working times. Two variables were also selected for showing a simpler bivariate correlation in Fig. 10, with the direct proportionality between areal RMS roughness and profile maximum height, which summarizes the same data clustering as in the PCA.

The archaeological samples fall into three groups in the score plot. The PCA did not highlight any morphometric fingerprint that could be referred to the different raw materials. Group I includes the PSTs possibly used for processing animal tissues (bones and soft tissues), according to the previous microscopic observations. Group I samples all have an RMS roughness around 100–110 μm and an average maximum height along profiles between approximately 150 and 180 μm. Group II clusters the PSTs that probably served for processing only plant tissue, in particular woody USOs; they display an RMS and mean roughness quite similar to those categorized in Group I, but differ for the parameters related to peak height, valley depth, and related distances, which are distinctively higher; however, one sample (Exc3-485) clusters in an intermediate position between different groups. Group III is characterized by markedly lower RMS roughness values, from about 50 to 60 μm.

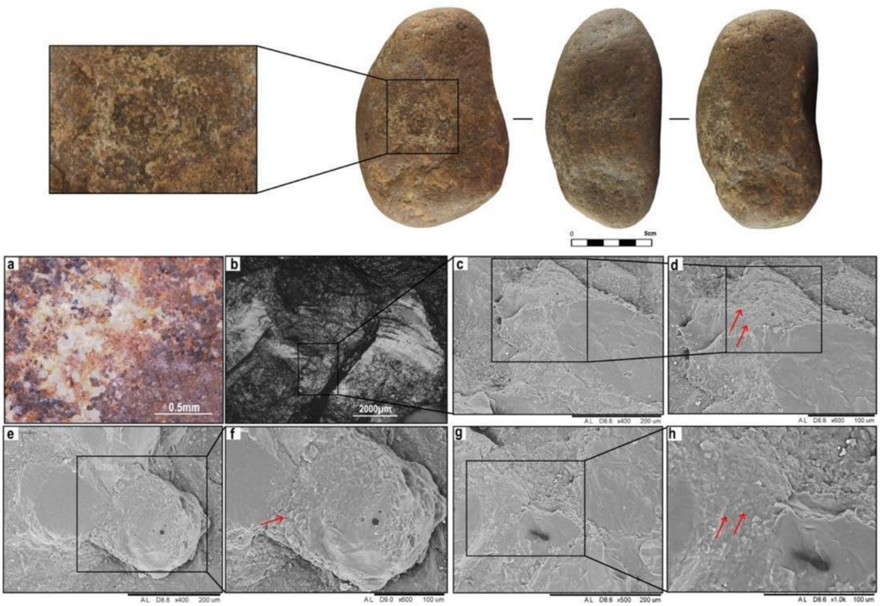

Fig. 8 A quartzite PST from Nyayanga (field number Exc3-103). The use-wear is indicative of the processing of bone tissues and probably soft tissues (possible multifunctional tool). This is evidenced by (**a**) the presence of percussion marks, (**b**) the appearance of a rough-domed micro-polish on crystals observed under a metallographic microscope, and (**c-h**) the smooth-flat polish observed on previous cracks on the crystals, as seen in SEM images

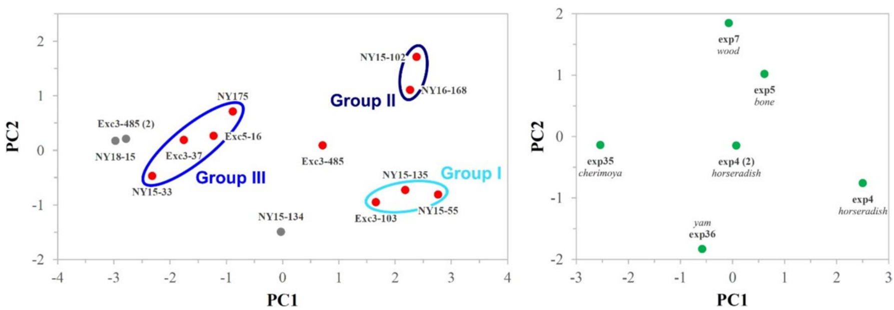

Fig. 9 PCA score plots from six morphometric parameters (RMS roughness *Sq*, max peak height *Sp*, max valley depth *Sv*, max height *Sz*, average max valley depth *Rvm*, average max peak height *Rpm*) calculated on 2×2 mm areas including roughness together with waviness (Supplementary Information_2; Supplementary Information_3). The archaeological samples are indicated by red dots (outliers in grey) and the experimental samples by green dots and the name of the material processed. The morphometric data of the two types of samples are not directly comparable as detailed in the text, so they were processed by two separate PCAs, based on the same parameters but different mathematical relations (PC1 and PC2 account for 75 + 13 = 88% and 45 + 28 = 73% of the total variance for the archaeological and experimental samples, respectively). Experiment nomenclature: Exp35 – *Annona cherimoya* (custard apple); Exp4 – *Armoracia rusticana* (horseradish); Exp36 – *Dioscorea* spp. (yam); Exp5 – *Ovis aries* (sheep femur and ribs with attached flesh and tendons); Exp7 – *Corylus* spp. (hazel tree)

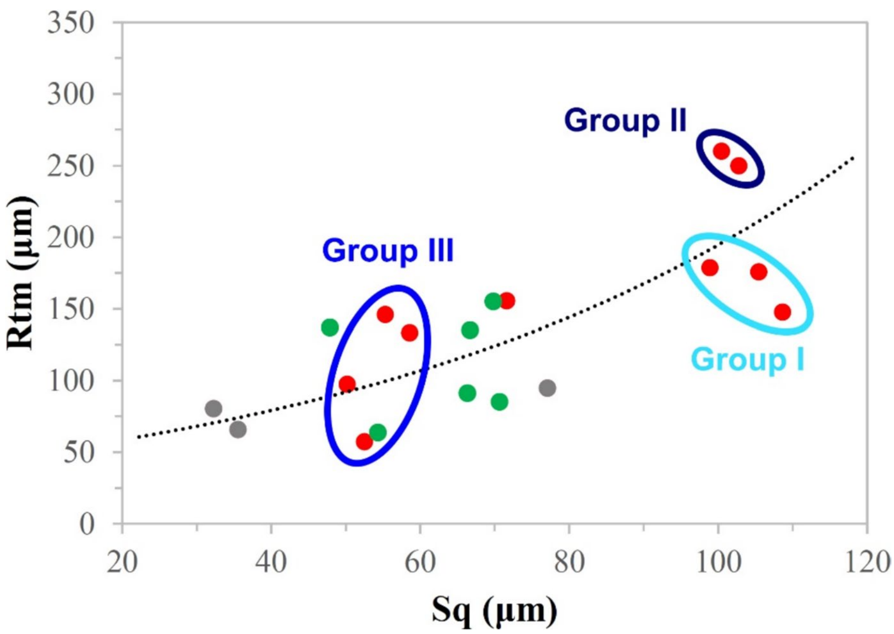

Fig. 10 Average max height (*Rtm*, measured on profiles) vs. RMS roughness (*Sq*, measured on areas) calculated on the maps of the archaeological (red dots, with outliers in grey) and experimental (green dots) samples

The qualitative analysis suggests that these artifacts were likely used for processing softer materials, that is, pulpy USOs. Finally, the score plot highlighted the presence of few outliers. NY18-15, supposedly used for the processing of animal material, scores outside the relevant Group I, probably due to pitting features observed on its surface. NY15-134 does not score nearby any cluster, because of its high surface alteration, which complicated the microscopic observations. Similar post-depositional traces may apply to the outlier Exc3-485 (2), which is in a more altered area. All in all, post-depositional modification appears to represent the most important limiting factor to the quantitative analysis.

The number of experimental samples is not high enough to show any statistically significant PCA clustering. However, the separation among the following materials can be recognized: (1) The experiments involving the crushing of soft vegetables (maracuja and yam) record the lowest RMS roughness values, around 50 µm. (2) The experiments with medium-hard to hard plant tissues (woody USOs and wood) and animal bones and meat are characterized by an RMS roughness around 70 µm.

Finally, simple bivariate analysis suggests interpretative possibilities and issues associated with PST use time (Fig. 10). Experimental PSTs used to process soft and harder materials cluster close to archaeological Group III—the PSTs used to process soft tissue samples. This may reflect a shorter usage time and an early developmental stage of surface roughness for the experimental PSTs. That is, this clustering suggests that the NY PSTs were intensively used for longer time periods than the experimental PSTs. Moreover, this also represents both methodological and interpretative issues in comparing known experimental PSTs use times to those of archaeological tools where the use time is unknown. Whereas microscopic analysis of the use-wear traces could identify the material category processed by the experimental PSTs, the material category was less easily resolvable with the quantitative approach because limited times of the experimentation constrained measurable trace development.

Discussion

Methodological Contributions and Analytical Advances

This study employs a comprehensive approach, combining qualitative and quantitative analyses, to understand the function of Nyayanga's PSTs. The wider distribution of use wear of the archaeological sample compared to the experimental sample is expected due to the greater variability in raw materials, functional activities, and post-depositional processes, which contributed to increased heterogeneity in surface modifications. As with all experimental analogues, our PST experimental sample is more controlled, focusing on specific conditions, but it cannot capture the full range of variations likely present in ancient contexts. However, the experiments were designed to isolate key functional patterns and diagnostic traces that can be related to categories of processed materials.

Within this analytical framework, the qualitative methodology integrates traces observed at varying levels of magnification, facilitating the identification and description of diagnostic wear patterns. This integrative qualitative analysis was a necessary first step in defining the extent and nature of post-depositional alterations on archaeological artifacts and how they affected use-wear features. Our qualitative analysis shows that distinct suites of traces allow confident identification of PSTs used to fracture bone and those used in pounding plant tissue, particularly (USOs).

In some instances, use-wear developed not on the fresher flaked surfaces, but on the cobble cortex. This use-wear modifies and is imprinted on natural cortical alterations, which were present at the time of use. Recognition of this is critical for the quantitative analysis using profilometry. It is essential to accurately distinguish between natural alterations and those created through use to prevent incorrect evaluations. Currently, quantitative methods alone cannot fully analyze a large set of artifacts as they require selective inclusion based on raw material similarity (such as fine-grained materials) (Ibáñez and Mazzucco, 2021). This selective approach can result in the exclusion of a significant portion of the assemblage, possibly limiting its interpretive value. The characteristics of the raw materials used to craft tools can impact the quantification of use-wear polish (Lerner et al., 2007). The most viable strategy to address natural alteration is excluding from analysis those tools with significant post-depositional alterations (Martisius et al., 2020). In our study, qualitative analysis is important for preserving assemblage variability and overcoming quantitative method limitations with large-scale sample sets. The qualitative record provides essential data on employed gestures (e.g., pounding-thrusting percussion), type and hardness of worked material (Adams et al., 2009; Adams, 1988, 2014; Hamon, 2006).

The limits of use-wear quantitative analysis are related to several factors. First, there is a lack of standardization in how measurements are taken (from the choice of the best performing technique to the analytical conditions) and in data processing methods (leveling, filtering, etc.), which greatly affect the reproducibility of textural data. Second, the relatively low number of quantitative datasets available in the literature complicates evaluation of the relative contributions of different wear traces, raw materials, and post-depositional alterations. Future work is needed to address these issues. Solving these issues would give a great boost to quantification methods, which might finally be applied on a large scale, providing consistent, accurate, and reproducible data, while possibly making qualitative analyses and wear interpretation shorter.

These findings lead to three important recommendations to produce research advances: 1) standardization of the acquisition and processing methods of morphometric data from archaeological materials; 2) the publication of the complete morphometric datasets collected before and after the most "destructive" steps of map processing; 3) careful choice of the size of the mapped area with the aid of microscopic observations, to control data variability.

In our case study, the application and the comparison of the qualitative and the quantitative analyses allowed us to obtain coherent results that confirm the presence at Nyayanga of two main PST functions: plant and animal tissue processing. The hypothesized soft tissue traces observed on the Nyayanga PSTs are consistently associated with bone processing. Therefore, we cannot exclude the possibility that these traces result from the presence of residual meat adhering to the bone rather than direct meat pounding.

The quantitative analysis suggests that some alterations (pits) observed on quartz crystals (i.e., field number NY18-15 associated with the processing of bone and soft tissues according to qualitative analysis) might have been erroneously correlated in the PCA with the use-wear resulting from plants exploitation activities, which may display somewhat similar pitting features (alterations) (see SI,Fig. 1). This consideration should be approached with caution in future analyses. We will improve further our preliminary test to expand the range of considered variables, encompassing raw materials, alterations, and worked materials. This reinforcement of the protocol and the combination with qualitative analysis aims to enhance data standardization, which constitutes the primary objective in the application of quantitative methods.

Implications for Early Hominin Behavior at Nyayanga

The PSTs from Nyayanga in Kenya reveal new data on the subsistence strategies of hominins in the late Pliocene, that involved processing plants/underground storage organs (USOs) and animal tissues. Faunal and stable isotopic analyses indicate that the Nyayanga archaeological site was situated in well-watered habitats with some trees, similar to other late Pliocene archaeological occurrences. This setting provided Nyayanga hominins with a diverse array of plant and animal foods, shelter, and potable water (Plummer et al., 2023). Furthermore, evidence of the butchery of a range of animals, including hippopotamids and bovids, provides clear indications of animal carcass exploitation. Fossilized bones from NY-1 with cut marks and percussion damage show that hominins were consuming both meat and marrow (Plummer et al., 2023). The exploitation of animal carcasses may have facilitated a faster acquisition of high-value animal proteins, achieved through the heavy fragmentation of bones using PSTs, enabling easier nutrient extraction (Thompson et al., 2019; Wolverton, 2002). The marrow thereby obtained is readily consumable, highly nutritious, and certainly represents the most easily obtained source of bone fat (Landon Karr et al., 2005).The presence of wear marks on Nyayanga percussive stone tools supports the idea that early human ancestors processed plant materials, specifically underground storage organs (USOs) like roots, tubers, and rhizomes. The predominant energy source in USOs consists of carbohydrates. Processing by PSTs likely aimed to make fibrous and tough parts of these plants more edible, facilitating access to increasing amounts of digestible nutrients and energy (Wollstonecroft, 2011). USOs offer a consistent food source during times when seeds and fruits were unavailable (Conklin-Brittain et al., 2006; Laden & Wrangham, 2005; Wrangham et al., 1999). These storage organs concentrate and store both nutrients and water underground, especially during periods of poor above-ground plant growth, making USOs particularly nutritious precisely when other above-ground plant parts are least available and least nutritious. To evade predation, plant storage organs are typically situated underground, often at significant depths, reducing competition with the animals that can access them (typically hominins, suids and mole rats) (Wrangham et al., 1999).

At Nyayanga, it is evident that hominins utilized PSTs for food processing. Pounding aimed to tenderize and fragment food, significantly reducing the use of masticatory muscles needed for consuming USOs. Experimental tests conducted by Zink and Lieberman (2016) indicated that pounding had no discernible impact on the ability to chew meat, but it notably decreased the average muscle engagement during USO consumption by 4.5% per chew ($P < 0.05$) and 8.7% per sample ($p < 0.05$).

Nyayanga PSTs typically have functional areas along short edges or on high ridges. The localized and non-random distribution of the use-wear pattern suggests a form of optimization in their usage and efficiency. Furthermore, the localized distribution of the wear patterns may indicate a controlled and repeated use of the tool, possibly reflecting a firm grip and targeted motion. Notably, the archaeological PSTs exhibit substantially more developed use-wear compared to our experimental specimens, which were employed continuously for approximately four hours. This disparity suggests that the Nyayanga tools were either used for significantly longer durations, subjected to more intensive force, or both. These findings imply that early hominins invested considerable time and effort in percussive tasks, possibly reusing tools across multiple activities or visits to the site. Such sustained tool use reflects not only technical competence but also planning depth and a flexible behavioral strategy suited to the ecological context of the Homa Peninsula.

While PSTs might be less sophisticated in craftsmanship compared to chipped stone tools, they prove effective and productive, reflecting a deliberate selection of tools showing strategic choices for acquiring and managing resources. This is further supported by the preferential transport of durable nonlocal cobbles to Nyayanga for tool use (Finestone et al., 2025).

Conclusion

The multidisciplinary approach combining qualitative macro/micro use-wear analysis and quantitative 3D surface analysis presented here contributes to a functional reconstruction of Nyayanga's Percussion Stone Tools (PSTs) used between ca. 3.0 and 2.6 Ma in eastern Africa. We identified clear evidence of percussive activities primarily associated with the processing of plant (e.g., USOs) and animal materials in modern comparative experiments. The integration of these methods enabled a robust functional interpretation across a wide range of raw materials, including quartz, quartzite, rhyolite, and allows for a clear distinction between use-wear traces and post-depositional processes.

These findings provide significant data into early hominin behavioral strategies on the Homa Peninsula. The intensity and spatial distribution of wear on PSTs support the interpretation of Nyayanga as a locality of repeated visits and activity, where hominins engaged in persistent resource exploitation. This underscores the central role of percussive technology within a flexible and diversified subsistence repertoire. While a multifunctional use of some tools—including for flake production—cannot be entirely ruled out, the use-wear evidence clearly documents functionally diagnostic traces related to pounding activities. Overall, this study highlights the significance of PSTs in shaping early hominin lifeways and contributes to a broader understanding of technological adaptation in the late Pliocene.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10816-025-09744-2.

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Author Contribution All authors contributed substantially to this work. I.C. and C.L. conducted the use-wear analysis; L.G. performed the quantitative analysis using profilometry; T.W.P., E.M.F., C.M., L.B., J.S.O., R.N.K., P.W.D., and R.P. contributed to the writing, critical review, and editing of the manuscript.

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Data Availability No datasets were generated or analyzed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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