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# Replicative experimental use of Palaeolithic Ground Stone Tools: Tracing and quantifying wear

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ABSTRACT

Advancements in microscopy technology have supported the traceological community in the pursuit of developing a quantitative approach in the field of use-wear analysis. The application of profilometry as a typical tribological tool, by providing micro-topographical scanning of artefact surfaces, has significantly expanded our capabilities, allowing us to (i) capture highly detailed micro-to-submicron-scale surface texture features, and (ii) attempt the calculation of various quantitative indices for characterising surface topography. The acquisition and statistical analysis of micro-topographical maps of the surface pose challenges when applied to Ground Stone Tools (GSTs), given their inherent petrographic and geometrical characteristics, as well as the diverse tasks these tools might have been involved in. In this pursuit, experimental replicas become indispensable, laying the groundwork for meaningful comparisons. By organising experiments sequentially and capturing surface texture at various stages of the replicative use, we achieve a dynamic comprehension of the evolution of the selected features over time. This study specifically hones in on task-specific experimental GSTs employed for the processing of various plant organs selected among those present across the Pontic steppe during the Marine Isotopic Stage 3 (60–25 kyr). Exploiting confocal profilometry, the data acquired support a robust quantitative approach, enabling the discernment of specific features and trends linked to the treatment of different plant organs. This methodological advancement plays a key role in distinguishing the varied activities undertaken by these tools, thereby establishing a fundamental basis for future comparisons with archaeological artefacts and eventually contributing to expanding the range of tool use in the Palaeolithic.

## 1. Introduction

In archaeological lithic studies since the 1990s, various efforts have been made to achieve a quantitative description of tool's surface texture (for discussions, see Stemp et al. 2016 and the literature therein). These efforts have been motivated by the need for univocal, objective descriptors and parameters shared among the scientific and archaeological communities, which aim to avoid subjective terms derived from qualitative approach to imaging data analysis and thus enabling the comparisons among different studies. This involves the use of various techniques for acquiring 2D surface profile data (e.g., Astruc et al. 2003; Stemp and Stemp 2003; Evans and Donahue 2008; Delgado-Raack et al. 2009; Bofill 2012; Bofill et al. 2013; Evans et al. 2014; Stemp 2014; Dubreuil et al. 2015; Gyurkovics et al. 2017; Macdonald et al. 2018; Delgado-Raack et al. 2022) and more recently 3D areal data (e.g., Goodall et al. 2015; Macdonald et al. 2019; Calandra et al. 2019a; Calandra et al. 2019b; Pedergnana et al. 2020; Zupancich and Cristiani 2020; Chondrou et al. 2021; Ibáñez and Mazzucco 2021; Paixão et al. 2021; Paixão et al. 2022; Sorrentino et al. 2023a). The latter allow the creation of detailed topographic maps that capture surface features at multiple scales of observation. However, it is important to note that previous efforts have predominantly concentrated on the analysis of the flaked industry. Applications to Ground Stone Tools (GSTs) have been limited, partly due to historically lower interest in this artefact category, which has only recently gained recognition for their high informative value as suitable multitasking tools. Additionally, distinct analytical

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constraints and inherent characteristics of the artefacts pose challenges to the application of quantitative and statistical approaches. Unlike flaked tools, which generally feature a uniform composition and limited variation in terms of raw materials, tasks, and textural characteristics within the same assemblage, GSTs display a high degree of variability in all these aspects. Moreover, while flaked tools typically have a primary working surface either parallel or transversal to their main axis, GSTs can present multiple working areas, displaying varying levels of use intensity. Upper Palaeolithic GSTs are typically pebbles and slabs composed of rocks with diverse minerals, displaying various textural characteristics, implying substantial differences according to the area analysed. The broad spectrum of tasks performed using GSTs adds another level of complexity to their surface analysis and eventual comparison. Each specific activity leaves distinct textural changes on the tool's surface, and when considering tools used for the same task, the variation in lithic composition further results in a diverse wear pattern (Delgado-Raack et al. 2022). Finally, within a given GST assemblage and when comparing different ones, there exists notable diversity in the types of rocks used, petrographic compositions, texture, and tasks performed. All these substantial variability poses a challenge in establishing a direct comparison. This complexity is compounded by the possibility of a single artefact being used for multiple concomitant or sequential secondary use, leading to a diverse array of trace types and patterns (Adams 2002: 21).

These aspects need careful consideration, especially when aiming for a mathematical description of very fine-scale surfaces using 3D areal data acquisition techniques, given the typically limited coverage area of these methods.

We present the application of a profilometry system and the analysis of areal surface parameters to assess the surface texture of experimental GSTs used in task-specific activities, such as the processing of various plant organs. The experimental replicas were designed according to a sequential strategy (e.g., Tringham et al. 1974; Brink 1978; Fullagar 1991; Lerner 2007; Hamon 2008; Ollé and Vergès 2014; Benito-Calvo et al. 2017; Pedergnana and Ollé 2017; Hayes et al. 2018; Sorrentino et al. 2023a), which considered measurements at multiple fixed experimental time intervals. The primary aim is to verify and quantitatively describe the evolution of use-wear patterns on the tool's surface. The analysis aims to determine whether this technique can effectively identify distinctive features and overall trends in surface modification, thereby shedding light on the different tribological mechanisms occurring during the varied selected tasks.

The utilisation of profilometer techniques and micro-topographical areal data in studying use-wear formation on replicative GSTs has been limited (Delgado-Raack et al. 2009; Procopiou et al. 2011; Bofill et al. 2013; Macdonald et al. 2019; Zupancich and Cristiani 2020; Chondrou et al. 2021; Paixão et al. 2021). Furthermore, only a smaller subset of these studies has focused on the elaboration of vegetal resources using different lithotypes, with specific attention given to acorns, cereals, legumes, and wild grass grains (Zupancich and Cristiani 2020; Chondrou et al. 2021; Paixão et al. 2021). Notably, these studies have considered tools made from limestone (Paixão et al. 2021), sandstone (Zupancich and Cristiani 2020; Chondrou et al. 2021), andesite, and granite (Chondrou et al. 2021). Our study extends this scope by encompassing various lithotypes, including sandstone, and introducing litharenite and quartz-arenite for which this quantitative approach has not been previously applied. Testing different lithic types is crucial, as each type of rock responds differently to mechanical stresses. Moreover, multiple vegetal resources and various plant organs were selected to be consistent with the resources available in the Pontic steppe during Marine Isotopic Stage 3 (MIS 3, 60–25 kyr) (Birarda et al. 2023). The resources were chosen based on their varying levels of resistance to mechanical processing and a range of characteristics, including dimension, greasiness, stickiness, wetness, stringiness, brittleness, crunchiness, and lightness, all aspects relevant for third-body abrasion. Consideration was also given to how these resources interact with the tool surface, such as scattering on the passive tool surface in the case of small and rounded resources (e.g., seeds or achenes) or adhering to tool surfaces for wet resources. The aim is to assess the degree of modification of GSTs' surface texture as a result of processing different media. Notably, the unprecedented choice to apply this quantitative approach combined with a systematic sequential replicative experiment proves pivotal in tracing the evolution of wear formation over time. Furthermore, establishing proxies for evaluating archaeological tools that account various stages of their use, facilitates subsequent comparative assessments and analyses of artefacts whose use-history is typically unknown. While we do not address the impact of post-depositional processes on the morphological characteristics of use-wear traces at this phase of the study, exploring the use stage of the tools' life cycle is fundamental to understanding the underlying processes driving wear development on GST surfaces and, consequently, through a comparative approach, inferring the function of the archaeological tools.

**Table 1**
Characteristics of the Leica DCM 3D objective lens 10× . The parameters for Numerical Aperture (NA), Field of View (FOV), Optical resolution and Vertical resolution, are reported.

| Objective magnification | NA | FOV (μm) | Optical res. (X/Y) (μm) | Vertical res. (nm) |
|---|---|---|---|---|
| 10× | 0.30 | 1270 × 950 | 0.47 | <30 |

## 2. Materials and methods

### 2.1. The equipment

To conduct the surface micro-topographic analysis, a confocal profilometer was chosen (Sorrentino et al. 2023a) due to the capability of the technique for the 3D reconstruction of selected regions, involving measurements and the calculation of indices to assess and understand the local phenomena of fracture and wear formation due to the cyclic use of the tools. The Leica DCM 3D dual-core measuring microscope available in the MUSAM-Lab at the IMT School for Advanced Studies in Lucca was exploited. This equipment was chosen mainly for its extensive surface measurement capabilities, ranging from several millimetres to a few nanometres, but also for its ability to analyse surfaces spanning from smooth to very rough, and for the high measurement speed, which is particularly useful for efficiently handling large collections. The profilometer system is equipped with the capability to analyse surfaces in both confocal and interferometry modes. The confocal mode has been selected here based on the range of microstructures to be observed and for the maximum amplitude of roughness to be characterised. Lenses with different magnification were employed, in order to achieve multiscale information on roughness and its evolution over time (see Borri and Paggi 2016, for similar applications to natural and artificial surfaces). The confocal objectives, featuring a higher Numerical Aperture (NA), facilitate the measurement of steep slopes, reaching a maximum local slope of 70 degrees. In this mode, the system achieves high-resolution measurements within the submicron lateral range and nanometre-scale vertical resolution. The confocal profilometer, employing a non-contact scanning approach, utilises distinct wavelengths of light directed at each point on the surface. By selectively capturing these focused wavelengths, automatically filtering out-of-focus information, and correlating wavelength and focal point distance the device can reconstruct the 3D topography of the surface, ensuring precise measurements of roughness heights (Bofill et al. 2013; Leica Microsystems 2023). To maintain stability during measurements, the equipment is placed on a passive vibration isolation base.

The 10× objective lens of the Leica DCM 3D (characteristics reported in Table 1) was found to be the best option to capture areas of 850 $\mu m^2$, whose size is optimal for the present application. Thus, the data

**Table 2**
The experimental GSTs under investigation, the analysed areas and the use-cycles considered for this study.

| ID | Task | Rock type | Analysed areas | Analysed T |
|---|---|---|---|---|
| GS7 | Passive tool. Achenes grinding | Litharenite | 2 squares: C4 at the centre of the used area; C2 in the peripheral region | 5 times: from $T_0$ to $T_4$ |
| GS8 | Active tool. Achenes grinding | Litharenite | 1 square at the centre of the used area | 5 times: from $T_0$ to $T_4$ |
| M2 | Active tool. Acorns pounding and grinding | Quartz-arenite | 1 square at the centre of the used area | 5 times: from $T_0$ to $T_3$ (including $T_{0.1}$ dedicated to the remotion of the acorns shells) |
| M23 | Passive tool. Acorns pounding and grinding | Quartz-arenite | 1 square at the centre of the used area | 5 times: from $T_0$ to $T_3$ (including $T_{0.1}$ dedicated to the remotion of the acorns shells) |
| M3 | Active tool. Dry roots pounding | Quartz-arenite | 1 square at the centre of the used area | 4 times: from $T_0$ to $T_3$ |
| M25 | Passive tool. Dry roots pounding | Quartz-arenite | 1 square at the centre of the used area | 4 times: from $T_0$ to $T_3$ |
| GS9 | Active tool paired with a wooden base. Achenes grinding | Sandstone | 1 square at the centre of the used area | 2 times: $T_0$ and $T_3$ |
| M7 | Active tool paired with a wooden base. Hazelnuts pounding and grinding | Quartz-arenite | 1 square at the centre of the used area | 2 times: $T_0$ and $T_3$ |
| M8 | Active tool paired with a wooden base. Dry roots pounding | Quartz-arenite | 1 square at the centre of the used area | 2 times: $T_0$ and $T_3$ |
| M12 | Passive tool. Achenes grinding | Quartz-arenite | 2 squares: 1 square at the centre of the used area; 1 at the centre of the ventral side | 2 times: $T_0$ and $T_1$ |
| M9 | Active tool. Achenes grinding | Quartz-arenite | 1 square at the centre of the used area | 2 times: $T_0$ and $T_1$ |
| GS3 | Passive tool. Various plants resources | Litharenite | 1 square at the centre of the ventral side | 2 times: $T_0$ and $T_4$ |

presented here includes only those collected with this lens.

## 2.2. Resources selection

As extensively detailed in Sorrentino et al. 2023a, ten stones were selected, paired and used as GSTs involved in task-specific activities, such as processing various plant organs for both nutritional and other daily tasks. These activities may include pounding and grinding plants organs to obtain flour, reducing their volume for easier transport and extended storage, softening them for easier elaboration, consumption and digestion, or separating fibres for a broad array of complements (e.g., Stahl 1989; Bofill 2012; Dubreuil and Nadel 2015; Longo et al. 2021). Therefore, parts of plants were selected that may require pre-treatment before utilisation/consumption, chosen from both underground storage organs (USOs) – roots, rhizomes, tubers, and bulbs – and above-surface storage organs (ASOs) – fruits, kernels, seeds, and leaves. Specifically, to cover a range of diversity in terms of resistance to mechanical processing and characteristics such as morphology, wetness, and oil content, we selected small seeds/achenes, shelled fruits, and roots from different plants. Our selections include *Rumex crispus* (curly dock) achenes, *Quercus* sp. acorns, *Corylus avellana* hazelnuts, *Cichorium intybus* roots, and *Armoracia rusticana* roots.

Prior to the use, the resources underwent diverse preparation procedures. Achenes were removed from the stems, while hazelnuts were cleaned of their husks but not from the nutshells. Roots were cleared of soil, lateral roots, and hairs, then cut into four pieces. All these resources were left to dry in open air for three months. Acorns had their pericarps removed. Half of them were oven-dried at 40 °C for 14 h, while the remaining were fresh-frozen to retain their water content (defrosted prior to use).

The stones for the replicative experiments were selected and collected from coeval Miocene and Lower Pliocene formations, along the middle basin of the Fiora River, near Manciano (Italy), and from the Racovăț River near the village of Brînzeni in the Edinet region (Moldova) (Sorrentino et al. 2023a). The Italian stones employed consisted of three litharenites: GS7, GS8, and GS3. The Moldovan stones, on the other hand, were the quartz-arenites M2, M3, M9, M12, M23, M25, and one graywacke, M5. The stones were designated as either active or passive tools, based on dimensions, shape, weight, and handling characteristics, and then paired accordingly. Specifically, GS3, GS7, M12, M23, and M25 were selected as passive tools and paired respectively with the active tools M5, GS8, M9, M2, and M3 (see Table 2 for a summary of the rock types and tool pairs).

In the design of the experimental collection, it was considered also the potential use of perishable materials, with a specific focus on wooden supports, owing to the ubiquity of this resource. Although evidence of woodworking is reported for Palaeolithic sites, the authors are not aware of any instances of wooden implements serving as ground tools in Pleistocene contexts. This lack of evidence may be attributed to the vulnerability of perishable materials in non-arid archaeological settings. However, the Palaeolithic site of Abric Romani (Spain, 49–45 uncal kyr) has yielded wooden flat, large artefacts, interpreted as dishes or containers for food (Carbonell and Castro-Curel 1992).

To explore this option, three additional tests were introduced, involving active lithic tools and a wooden plate with a small rim used as a passive implement, to treat the three different types of media identified: achenes, shelled fruits and roots. Specifically, the stones selected as active tools were GS9, a quartz-rich sandstone collected from the Fiora River basin, M7 and M8, two quartz-arenites from the Racovăț River basin.

## 2.3. The replicative experiment setup

The experimental replicas were conducted according to a sequential strategy involving multiple usage cycles, each lasting 30 min (designated as $T_x$). A fixed amount of 15 g of aerial and underground plant organs were processed in each replicative cycle, weighed using an Orma electronic model BC laboratory scale with a readability of 0.1 g and a maximum capacity of 5 kg (Sorrentino et al. 2023a).

At the end of each cycle, as well as at $T_0$ (the unused stage of the tools), we applied a standardised multiscale documentation and analytical strategy to perform trace analysis, as detailed in Sorrentino et al. 2023a and Sorrentino et al. 2023b. This strategy included the use of polyvinylsiloxane (PVS) molds to obtain a negative copy of the surface and permanently document the surface texture, following a well-established procedure in lithic tools studies (e.g., Longo 1994; Ollé and Vergès 2014; Pedergnana and Ollé 2017; Hayes et al. 2018; Zupancich et al. 2019; Chondrou et al. 2021; Longo et al. 2021; Longo et al. 2022; Sorrentino et al. 2023a). The copy capacity of molds and their reliability to conduct surface texture analysis has been tested by previous studies (Bofill 2012; Goodall et al. 2015; Macdonald et al. 2018; Delgado-Raack et al. 2022).

The replicative experiment was designed to last for three cycles.

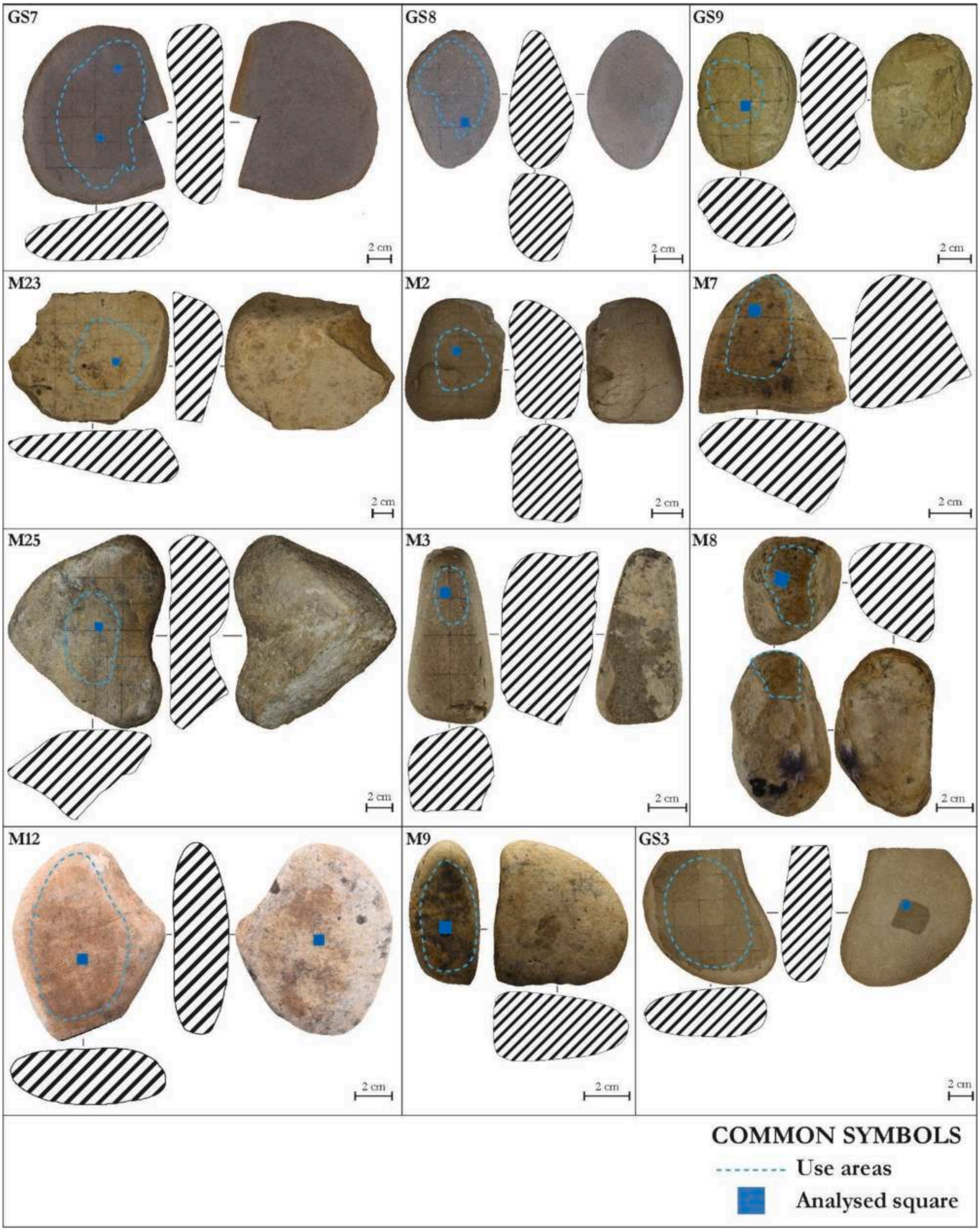

**Fig. 1.** Images extracted from the 3D models of the GSTs (Sorrentino et al. 2023a; Sorrentino et al. 2023b) investigated in this study, shown at $T_0$. It features the ventral and dorsal surfaces of the tools, along with sections extracted from the models. The light blue dashed lines highlight the areas directly involved in the task, extending to the last cycles of the replicative experiment, while the blue square indicates the analysed reference square (adapted from GS PhD thesis, Sorrentino 2023).

Therefore, for GS7-GS8, M2-M23, and M3-M25, which were associated with the three resource types – achenes/small seeds, shelled fruits and roots – the replicative tasks initially lasted for 90 min from $T_1$ to $T_3$, and analyses were performed at the end of each cycle.

However, during data analysis, specific questions arose regarding the behaviour of surface roughness, which exhibited cyclic changes (as will be presented further in the Results). To verify this dynamic for the GS7-GS8 pair, for which the phenomenon is particularly evident, one additional replicative cycle was added ($T_4$). Therefore, this pair of tools was used to grind *Rumex crispus* achenes for 120 min ($T_1$ to $T_4$). Achenes are a resilient resource, and for their transformation into flour, a predominant grinding motion, horizontal, bidirectional, and sometimes circular is needed. Due to their small and rounded shape, they scatter onto the passive stone surface as soon as they come into contact with the active tool, requiring frequent gestures to group and re-group them using either the free hand or the active tool itself. Their dispersal on the surface caused recurrent contact between the active and passive tools, only partially mediated by the presence of the medium. Additionally, also M9-M12 were designated to process *Rumex crispus* achenes. The selection of two different lithotypes used to process the same resource aimed to verify if there is a difference in the wear process related to the distinct characteristics of the stones. For the specificity of the question, only one cycle of grinding ($T_1 - 30$ min) was performed. Moreover, the ventral side (the face in contact with the soil) of M12 was also monitored, and molds were taken at $T_0$ and at $T_1$, the end of the replicative task.

M2 and M23 were selected to elaborate *Quercus* sp. acorns. The process began with the removal of the pericarp using the same experimental tools, marking this stage as $T_{0.1}$. Subsequently, the resources underwent three cycles of 30 min each ($T_1$ to $T_3$) of light pounding and grinding. The acorn chunks and flour did not scatter all over the stone's surface but remained grouped closer to the contact areas of both stones, mostly preventing direct contact between them.

M3 and M25 were assigned to process *Cichorium intybus* roots. Dry roots were pounded using short, fast, and repeated vertical movements, interspersed with axial rotation of the active stone on the root and wrist pressing in place to separate the fibrous portion. Towards the end of the process, horizontal linear grinding movements were employed to powder the obtained chunks. The contact between the stone surfaces was strongly mediated by the fibres and/or by the paste that derived from the processing and adhered to the surface, making the treatment of this resource more challenging. The process lasted three cycles, accumulating 90 min of use.

GS3 and M5 were utilised to transform various types of resources, including achenes, pods, and acorns. However, this test is solely discussed here in relation to the examination of the ventral side of the passive tool GS3. This face of passive GSTs experienced wear formation not directly ascribable to use but rather as a result of the blows and recoils absorbed during the task performed on the dorsal side. Similar to the analysis of the ventral side of M12, for GS3 this is also examined only at $T_0$ and at the end of the replicative experiment $T_4$.

In addition to the previously mentioned experimental replicas, tests were conducted considering also a wooden passive base paired with three different active stones. These tools were used in three cycles of 30 min each (totalling 90 min) to process the preselected plant organs — achenes, shelled fruits, and roots. In each cycle, GS9 and M8 were designated to process 15 g of dry *Rumex crispus* achenes and *Armoracia rusticana* roots, respectively. M7 was assigned to elaborate approximately 30 g of dry *Corylus avellana* hazelnuts per cycle. This process involved initially cleaning the hazelnuts from their shells, followed by pulverising the fruits within the same usage cycles. Kraybill (1977: 492) reports on the use of wooden mortars and pestles in ethnographic examples and classical archaeological contexts, purposefully involved in the processing of flour to obtain a desired fine-grained end product. Our study aligns with these findings, revealing an increase in tool efficiency when a wooden base is employed as a passive tool to process roots. Adherence to the wooden material is minimised compared to stone surfaces, resulting in easier resource processing. However, due to the smoothness and plasticity of wood, it has lower friction compared to stone, which reduces its effectiveness in transforming hard resources as achenes. Nonetheless, it is very effective in obtaining a cleaner and, therefore, finer grain flour, separating the coarse hulls of the achenes from the seeds.

## 2.4. Sampled areas for analysis

Before conducting the replicative experiments on all the stones, up to two 5 mm$^2$ squares were marked with permanent ink. These squares served as control references. When molds were taken, part of the ink was transferred onto the PVS, ensuring that the reference remained constant. This was punctually examined after each experimental phase, starting from the natural state ($T_0$), on both active and passive tools. Throughout all the replicative cycles, the analysed area remained consistent on the tool surface and, consequently, on molds, to trace the development of wear over time. The choice to draw it with permanent ink was made as the least invasive approach. Unlike other methods, such as scratching the sample (Stemp and Stemp 2003; Martisius et al. 2018) or attaching ceramic beads as reference points (Calandra et al. 2019b), the ink did not alter the stone's surface texture and, therefore, the development of micro-traces in the area. However, it is prone to depletion caused by the task in which the stone is involved. Therefore, frequent redrawing of the square was performed, possibly creating a certain degree of uncertainties in the analysis.

The location of the reference square on each stone was selected from $T_0$, before processing any resource (Fig. 1). As presented in Table 2 the square was placed at the centre of the surface preselected to be the working surface, where the contact with the material to be treated and eventually with the other stone is expected to be most intense. Additionally, to verify if there are substantial differences in the trend of surface modification between the central working area and a peripheral zone of the working area, a second square was drawn in one case, on the passive implement GS7. Furthermore, as already mentioned, to verify whether wear also developed on the unused ventral surface of the passive tools, two additional surfaces were considered in this study on GS3 and M12, with both the initial state ($T_0$) and the final time of use analysed.

## 2.5. Data acquisition and processing

As already reported, the 10× lens of the Leica DCM 3D confocal profilometer allowed to scan squares with an area of 850 μm$^2$. Given that the reference square drawn on the stone surfaces were of 5 mm$^2$, we scanned around twenty-five areas within this reference square. However, since the scanning process involves operator-controlled movement of the stage, the exact number of squares and exact scanned area may vary slightly from one T to the sequent one.

Among the twenty-five scanned areas, nine squares on each surface under evaluation (approximately one-third of the total acquired areas) were selected for data analysis, employing the open-source software Gwyddion (version 2.59; Nečas and Klapetek 2012). As the molds represent the negative copies of the surfaces, data acquired on them were inverted on the z and flipped along the x-axis before analysis to simulate conditions on the actual tool surface. Additionally, a de-trending based on the subtraction of the average plane has been made to remove the effect of a non-planar tool. The small size of each analysed square (850 μm$^2$) and the selection of nominally flat areas situated in the centre of the working surface, away from the curvature of the stone edges, render curvature de-trending unnecessary in this case.

Utilising surface micro-topographic 3D maps, standard statistical parameters for areal characterisation were computed (e.g., Astruc et al. 2003; Stemp and Stemp 2003; Evans and Donahue 2008; Delgado-Raack et al. 2009, 2022; Bofill 2012; Bofill et al. 2013; Evans et al. 2014; Stemp 2014; Stemp et al. 2016; Calandra et al. 2019a, 2019b; Caricola et al.

**Table 3**
ISO 25178-2 surface texture areal parameters.

| Parameter | Meaning |
|---|---|
| Sa [μm] | Arithmetical mean height of the surface |
| Sq [μm] | Root means square height of the surface |
| Ssk [-] | Skewness of height distribution |
| Sku [-] | Kurtosis of height distribution |
| Sp [μm] | Maximum height of peaks |
| Sv [μm] | Maximum height of valleys |
| Sz [μm] | Maximum height of the surface |

2018; Macdonald et al. 2019; Zupancich and Cristiani 2020; Paixão et al. 2021, 2022; Sorrentino et al. 2023a).

Specifically, this study computed the Surface Heights Distribution, which gives the number of points on the surface with a given height value (Blateryron 2013), and ISO 25178–2 surface texture areal parameters (refer to Table 3). The most influenced parameters by the wear process on surface roughness are the Arithmetical Mean Height (Sa) and the Root Mean Square Roughness (Sq). The wear process leads to a gradual smoothing of surfaces, noticeable as a decrease in these parameters. Conversely, an increase in Sa and Sq could signify localised micro-fracture events of the brittle stone. These fractured asperities are typically rougher than the worn ones (Blateryron 2013; Calandra et al. 2019a). Specifically, Sq provides insights into the standard deviation of surface height distribution with respect to the average plane. In contrast, Sa denotes the absolute difference in height for each point compared to the surface average. While these parameters are interrelated, Sq is considered statistically robust and widely used in contact mechanics. Consequently, the subsequent paragraph does not discuss the Sa parameter.

It is worth noting that the software does not compute Kurtosis directly but provides the Excess Kurtosis value. This computation assumes a Gaussian data distribution as 0 rather than 3 (Nečas and Klapetek 2012).

Moreover, since the above traditional statistical roughness parameters may depend upon the resolution of the instrument used to acquire the surfaces (Majumdar and Bhushan 1990; Zavarise et al. 2007), the Power Spectral Density (PSD) function was computed for selected areas on all the actively used sides of the GSTs that underwent surface modifications during their use. The differences between $T_0$, representing the pre-wear state, and $T_1$, after sufficient use to observe surface modifications, were analysed. The relationship between the PSD and spatial frequency reveals all the scale-invariant features of surfaces, particularly the roughness content at each scale.

## 3. Results

Upon the examination of the data, it becomes apparent that the initial roughness of the stones markedly varies when comparing those gathered from the Fiora and Racovăț rivers. The average Sq data for the analysed Moldovan stones is 23.2 ± 5.7 μm, while the Italian stones present a Sq average value of 39.8 ± 6.4 μm (Fig. 2). The use of the tools in grinding or grinding and light pounding actions resulted in a reduction of roughness for both active and passive tools, which is a typical effect of wear. An exception is noted for the stones used to treat dry roots, M25 and M3, where the roughness experiences an increase while performing the task. This can be explained by noting that the processing of this resource, primarily through intense pounding actions, may induce localised crack formation and the exposure of new surfaces, leading to an increase in Sa and Sq values at certain time intervals.

For all the analysed experimental GSTs, the most significant difference in Sq is observed between the used and unused states, measured in this study after 30 min ($T_1$). In the subsequent phases of use and consequent wear formations, small non-monotonic oscillations over time are evident, likely attributed to alternating cycles of surface texture levelling and damaging pattern formation.

The pair GS7 and GS8, used to treat achenes, exhibits the most significant difference between the $T_0$ and $T_1$ stages. The litharenites are indeed less resistant to mechanical stress than quartz-arenite. It is important to recall that achenes are small, rounded, and resilient resources that scatter onto the passive tool's surface, resulting in frequent stone-to-stone contact during grinding. This leads to intense and extended wear formation, visible even to the naked eye. It is also noteworthy that the two measured squares on GS7 exhibit different behaviours. After an initial decrease in the Sq parameter, which is more pronounced in the central C4 square, the roughness in this area becomes relatively constant with small non-monotonic oscillations, while in C2, fatigue accumulates, and the roughness value decreases over time (Sorrentino et al 2023a). This also emphasises the importance of

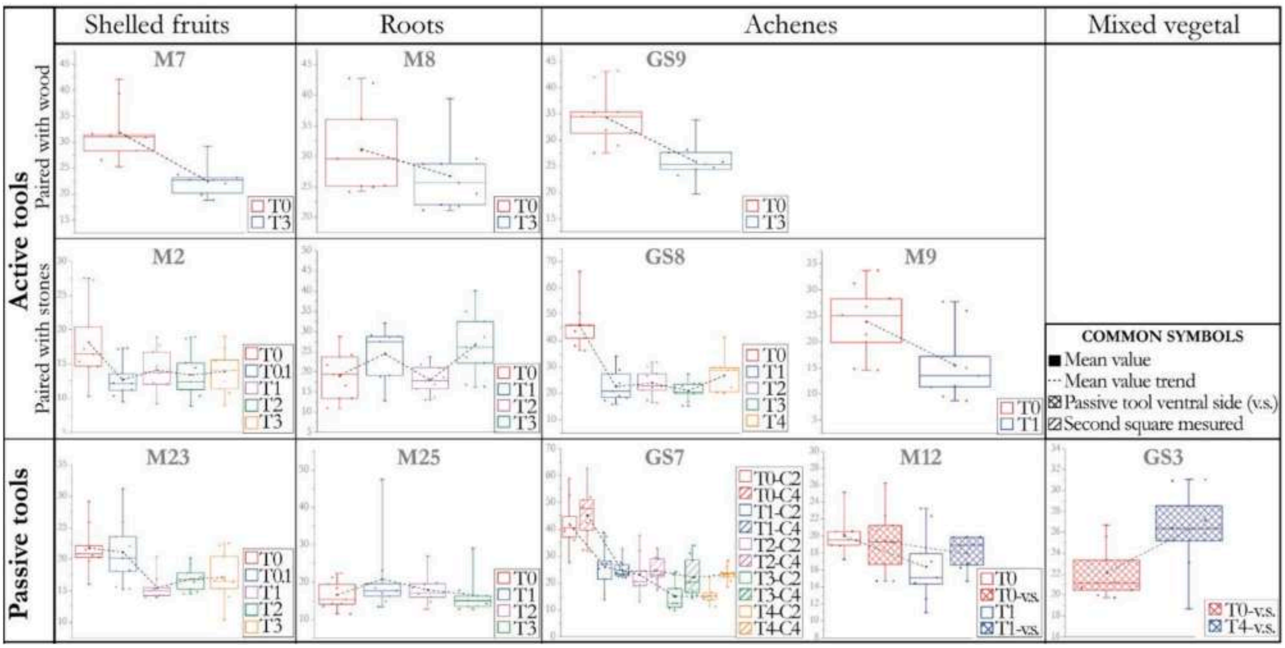

**Fig. 2.** Boxplot of the Sq parameter of the analysed experimental GSTs (adapted from GS PhD thesis, Sorrentino 2023).

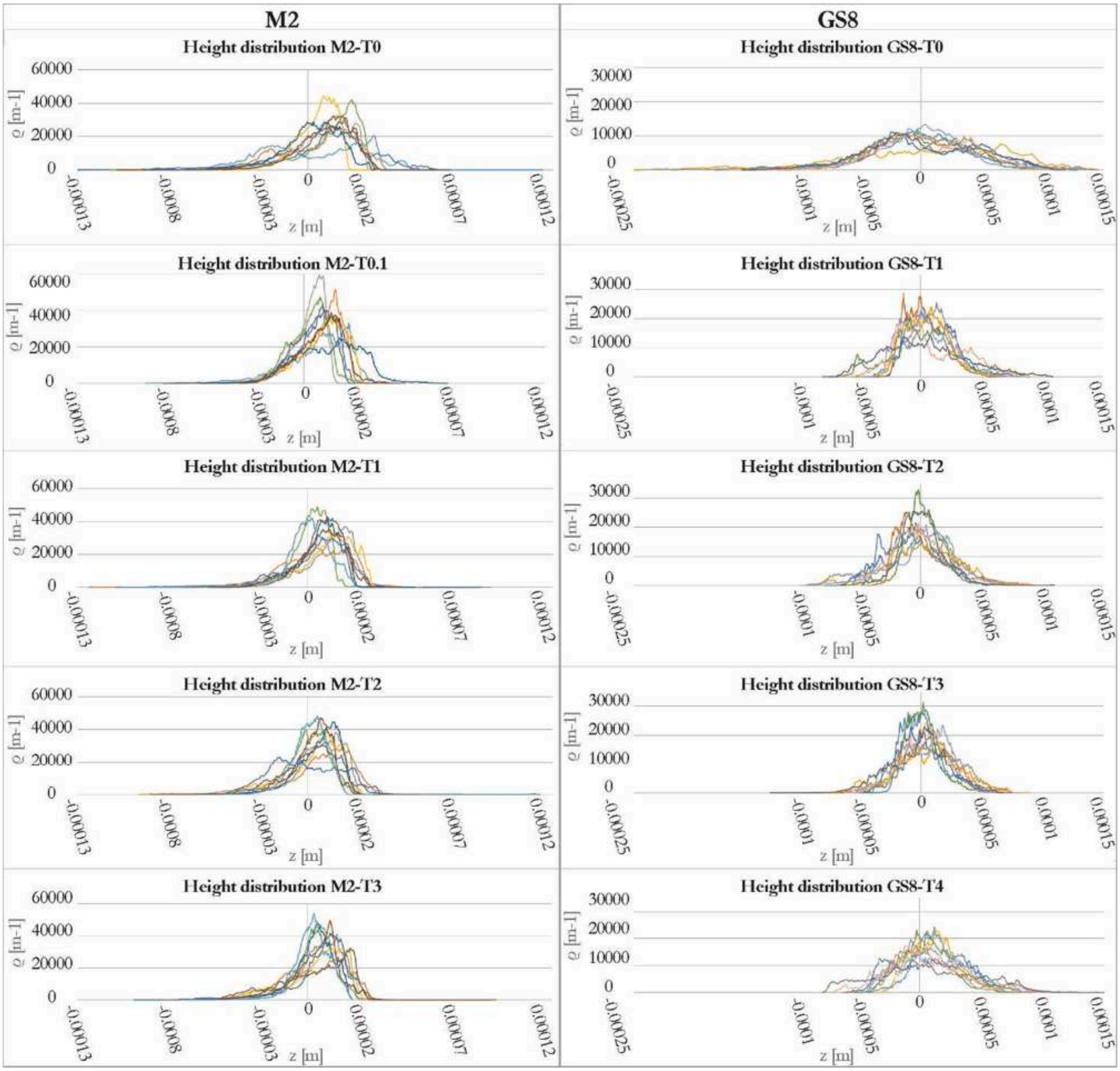

**Fig. 3.** Examples of height distribution for the two active tools M2 and GS8. M2 exhibits a Leptokurtic distribution with a moderate negative skewness at $T_0$, which becomes more pronounced with long tails at $T_1$. On the other hand, GS8 at $T_0$ shows a Gaussian data distribution, which slightly shifts towards a Leptokurtic distribution, especially at $T_3$. The Ssk is around 0 initially, shifting slightly towards positive values with use (adapted from GS PhD thesis, Sorrentino 2023).

carefully selecting the analysed area and, ideally, choosing more than one area, as the results strongly depend on the sampling strategy and the specific location of the analysed square.

In the case of M23, the passive tool used for acorn elaboration, the first 30 min of use ($T_{0.1}$) did not significantly affect the surface. However, this stage represents only the removal of the pericarp of the fresh acorns, and therefore, the stress on the passive tool was minimal.

Regarding the active tools paired with the wooden base, all demonstrate a decrease in roughness parameters after use. However, this reduction is less pronounced compared to the data presented for their corresponding active tools paired with lithic passive tools. This discrepancy can be attributed to the lower resistance, smoothness, and plasticity of wood, which result in reduced friction compared to stone. Among these GSTs, M8, the tool used to treat dry roots, exhibits the least intense modification. The elaboration of this resource has the least impact on wear development.

All the stones display a height distribution at $T_0$ with a Gaussian shape, featuring Sku values around 3 (indicating an excess kurtosis around 0) or a Leptokurtic distribution (Sku > 3), showcasing a symmetrical shape resulting in Ssk values around 0 or moderate negative skewness (e.g., Fig. 3). After use, the examination of the working surfaces indicates that these parameters did not experience substantial changes, except in the case of the Sku values for M2 and M12, where a significant increase is observed (Fig. 4).

The values of Sp, Sv, and Sz exhibit considerable variability among the analysed samples (Fig. 5). When comparing Sp and Sv values for the stones in their natural state, it is evident that valley values consistently exceed peak values. Stones collected from the Fiora River show the highest surface amplitude, with an average Sz of 254 ± 36 μm, while stones from the Racovăț River have an average Sz of 171.4 ± 26 μm. Both parameters tend to decrease after tool usage on the utilised side of the GSTs. The Italian stones demonstrate a rapid, progressive smoothing of the texture, resulting in a notable reduction of Sp and Sv values. This process is much less pronounced in the pebbles collected from the

**Fig. 4.** Boxplot of the Ssk and Excess Kurtosis parameters of the analysed experimental GSTs (adapted from GS PhD thesis, Sorrentino 2023).

Racovăț River, particularly in passive tools. An exception is observed for the pair of Moldovan tools used to treat dry roots, presenting an increase in the values for the active tool M3, attesting the formation of pits and cracks on the surface during the treatment of roots. For the passive tool M25, the parameters remain relatively constant, confirming the less pronounced impact of this resource elaboration on wear formation compared to the treatment of other vegetal resources.

The ventral side of the passive tools, measured for M12 and GS3, exhibits different behaviour compared to the used dorsal faces. In the case of M12, this was measured after 30 min of use, and indeed, the differences are not substantial. The only parameters worth reporting are the variations in the Ssk and Sku data, whose values trend show the opposite behaviour to the used surface, with a slight increase of Ssk and a decrease of Sku. Regarding GS3, the use of the dorsal side of the stone, caused at the ventral side the increase in the Sq value, probably due to the blows and recoils resulting from the processing and the contact of the surface with the soil. The Ssk, Sku, and Sp values did not show significant variation between the use and unused stages, while the Sv, and consequently the Sz data, present a significant increase.

It is evident that from a tribological perspective, the proposed experimental tests are quite complex, as they involve repeated contacts between the two lithic surfaces and the third body in between. To investigate the multiscale properties of the surfaces, particularly the roughness content at each scale, the PSD function has been computed. This was analysed for a selected square for each tool that has been subject to surface modifications during their use, considering $T_0$ (as is, before occurrence of wear or microfracture) and $T_1$ (after a sufficient use to see surface modifications). Bilogarithmic diagrams relating the PSD to spatial frequency were then determined. Fig. 6 illustrates the comparison between false-colour maps of surface portions at times $T_0$ (left panels) and $T_1$ (right panels) for the four active GSTs: M2, M3, GS8, and M9. Similarly, Fig. 7 shows the comparison for the four passive GSTs: M23, M25, GS7, and M12. In the micro-topographic false-colour maps, peaks are represented in red and valleys in blue. The corresponding surface PSD functions, depicted in blue for $T_0$ and orange for $T_1$, are displayed on the side plots and are well described by power laws, except

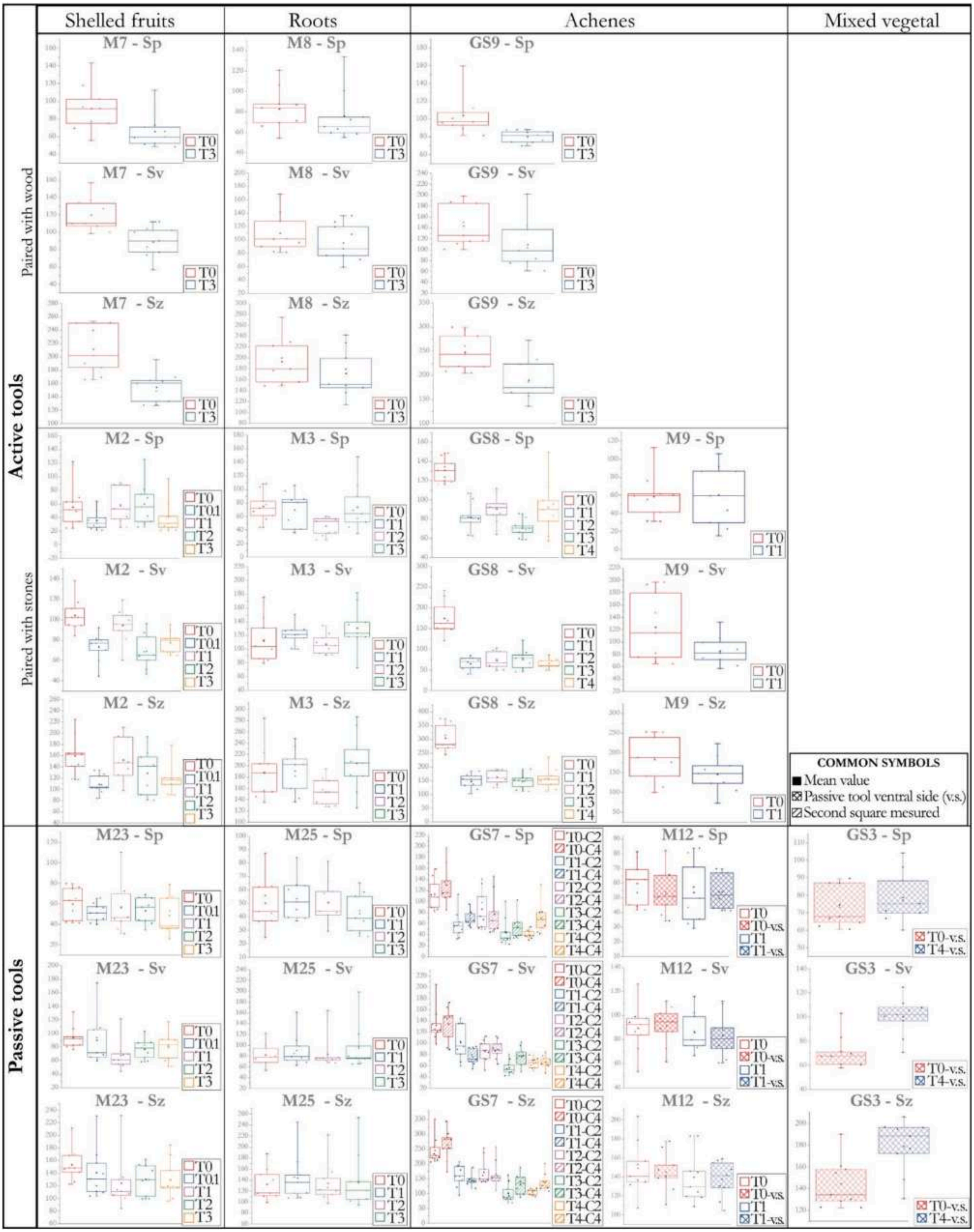

**Fig. 5.** Boxplot of the Sp, Sv and Sz parameters of the analysed experimental GSTs (adapted from GS PhD thesis, Sorrentino 2023).

for some flattening at large wavelengths (small frequencies).

In the case of M2-M23, quartz-arenites used to process acorns, the medium is much softer than the stone material. In case of achenes, they are characterised by small size and tendency to spread over the passive tool’s surface, which requires low contact forces spread over a large area to process them. Under these conditions, the type of surface evolution is typical of grinding and polishing actions in tribology, when a process of step-by-step reduction of roughness takes place due to the action of the

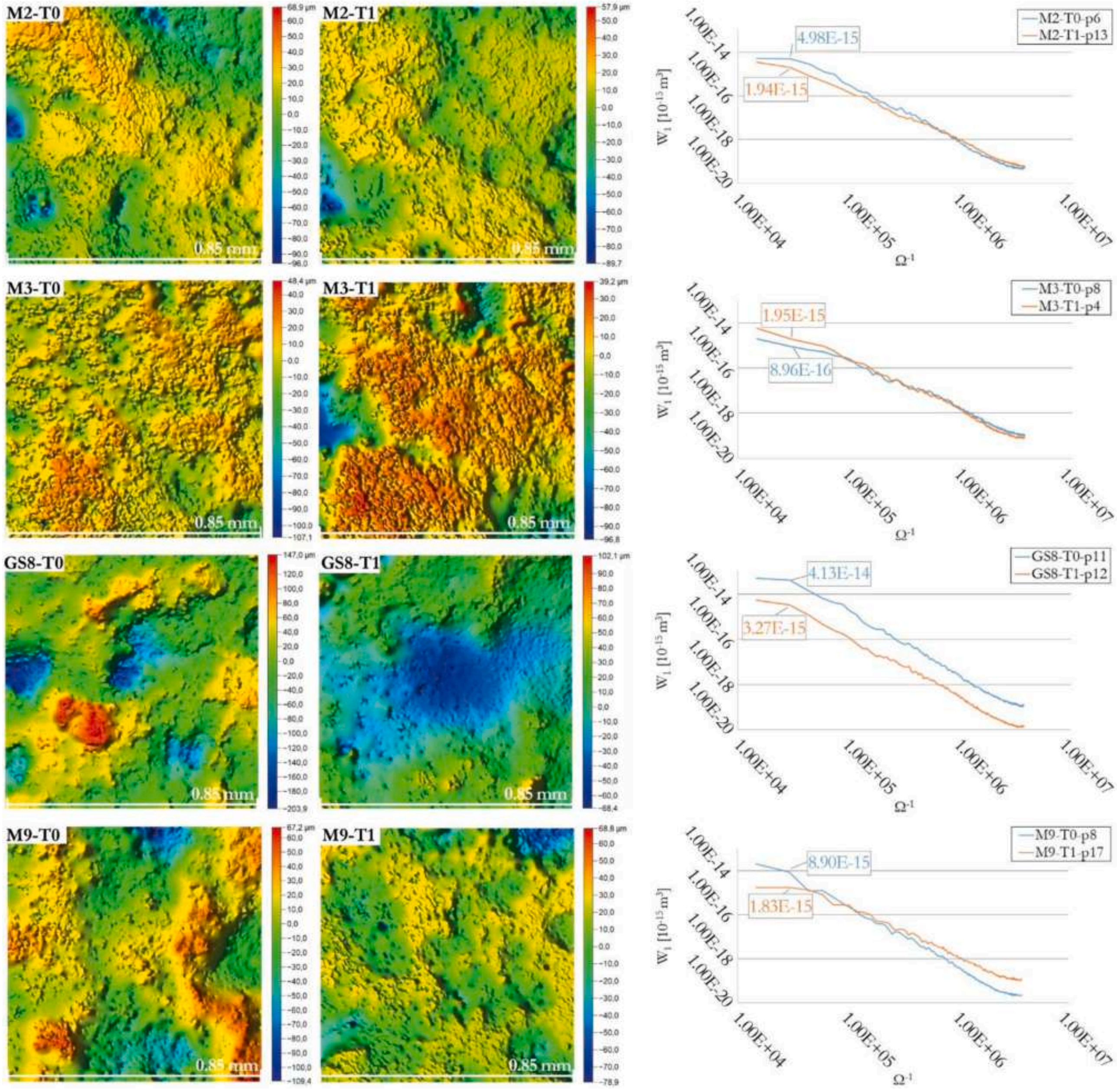

**Fig. 6.** Left: False-colour maps of a designated square on the used areas of the active tools at $T_0$ and $T_1$ are displayed. Right: The power spectral data for these areas are presented.

abrasive particles in progressively finer sizes. In such a case, the PSD function modifies especially in the low frequency regime, with a progressive flattening (see Paggi and Barber 2011). GS8, and to a slightly lesser extent GS7, experienced the most intense surface depletion over a wide zone during processing. This was primarily due to the behaviour and resistance of achenes as we discussed, as well as to the softness of the lithotype (litharenite). Consequently, the PSD functions at $T_0$ and $T_1$ for these tools do not overlap across the entire frequency range. However, the slope and shape of their PSDs remain largely unchanged, indicating that the wear process did not alter the exponent of the power-law PSD, which is related to the fractal dimension D (for GS8 $D = 2.25$ at $T_0$; $D = 2.24$ at $T_1$; while for GS7 $D = 2.27$ at $T_0$; $D = 2.24$ at $T_1$). Instead, it influenced the multiplicative coefficient of the power-law related to the root mean square surface roughness. For the pair M12-M9 used to treat the same medium, but made of resistant quartz-arenites, results do confirm, also in terms of PSD and not only in terms of the computed roughness parameters, the almost invariance of their surface features after use, since PSD functions at $T_0$ and $T_1$ overlap for most of the frequency range. However, M9 (previous studies have demonstrated that active tools undergo a more pronounced wear process during vegetal resource grinding compared to passive implements; Adams 2002: 119; Sorrentino et al. 2023b) present a cut-off to the PSD power-law trend for small frequencies, which is a typical effect of artificial surface finishing (polishing/grinding) operations in tribology (Paggi and Barber 2011) or, as in this case, of human induced use-wear process.

A different evolution over time is noticed for the pair M3-M25, with an increase in the content of roughness in the low frequency range, especially for M3 and to a minor extent also for M25, while the slope of the PSD remains almost unchanged. The two stones are made of the same quartz-arenite and used to process dry roots as third-body in between, which have higher adhesion than the previous resources and their processing requires higher impact forces of the active tool. The high stiffness and adhesion of the medium, combined with those processing conditions, are sufficient to induce a different type of surface

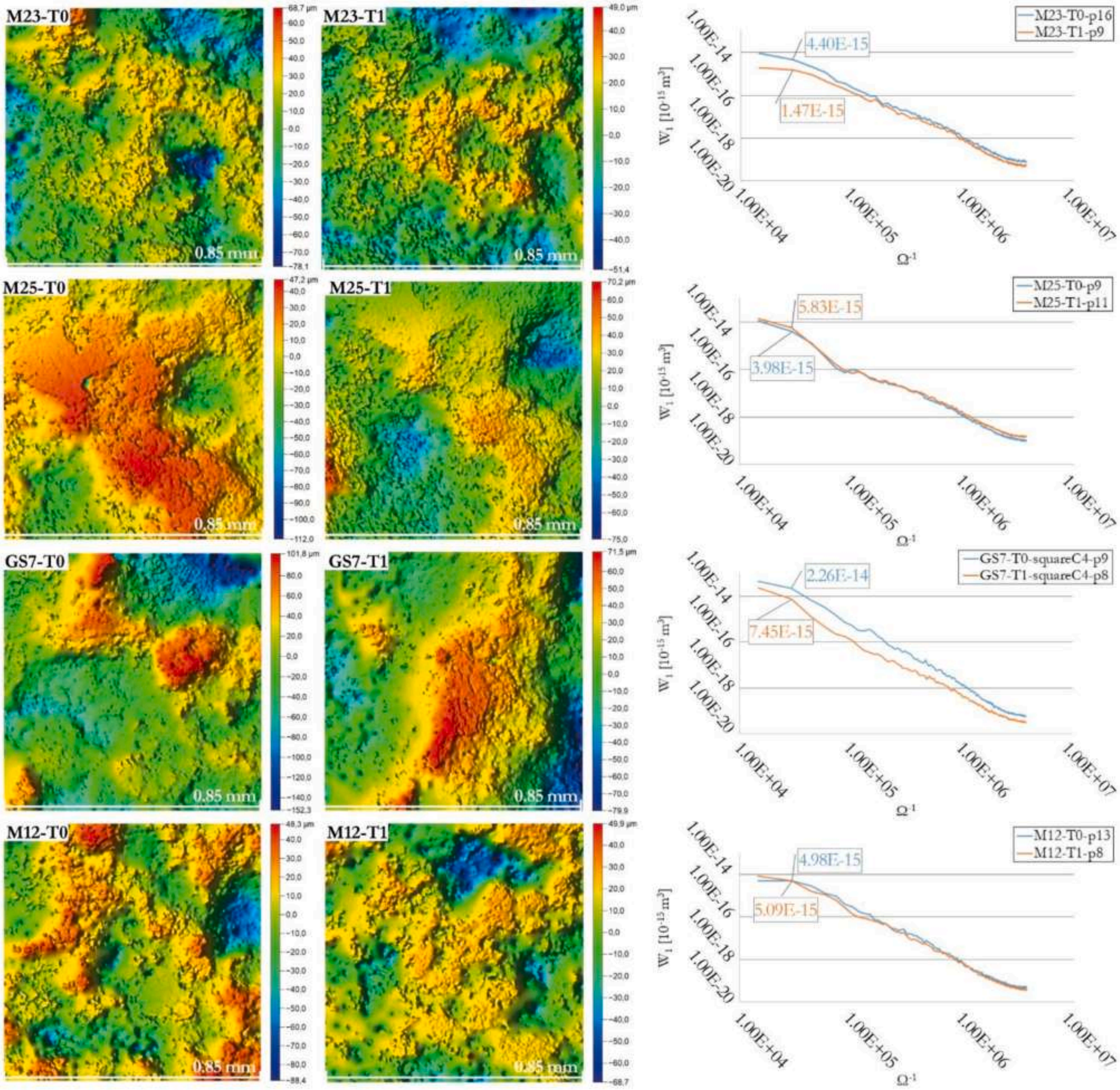

**Fig. 7.** Left: False-colour maps of a designated square on the dorsal side of the passive tools at $T_0$ and $T_1$ are displayed. Right: The power spectral data for these areas are presented.

damage as compared to polishing or grinding. As numerically investigated by Milanese et al. (2019) using molecular dynamics simulations, emergence of self-affine surfaces may occur during adhesive wear under special conditions. As they found, if the wear debris size is sufficiently small, then it can lead to fracture at the asperity level instead of plastic deformation and, as a result, the steady-state surface after wear can appear rougher than before. This can be compatible with the observed increase in the PSD content only in the low frequency range, thus leading to a single PSD slope typical of self-affine surfaces. The analysis of the PSD function of M3 leads to a fractal dimension $D = 2.39$, which is a value close to the range of $D = 2.1–2.3$ reported in the literature for self-affine fractured rocks (Candela and Brodsky 2016; Renard et al. 2019; Sagy et al. 2017).

## 4. Discussion and conclusion

The acquisition and statistical elaboration of surface areal data represent a reliable and quantitative approach for use-wear analysis, facilitating precise data collection and promoting informed interpretation. Nevertheless, when analysing the data —particularly in constructing a reference collection for comparisons to support the functional interpretation of archaeological artefacts— certain relevant aspects need to be considered.

The importance of selecting lithotypes compatible with the archaeological context is evident and has been demonstrated, as the raw material of tools influences their response to mechanical stresses during contact and the consequent development of fracture and wear. Additionally, the present study highlights the significant impact of the selected area for data acquisition on the overall analysis, emphasising the necessity of acquiring a sufficient number of areas to draw conclusions that are statistically robust. In this regard, the computation of the spectral density function of the surfaces, in addition to the standard statistical parameters of roughness, has been shown to be very useful to synthetically interpret complex surface evolutions within a multi-scale perspective. While this method is well established in tribology, especially in relation to the analysis of metallic surfaces in relative contact, its cross-disciplinary application to quasi-brittle stones for archaeological investigations is unprecedented and can be considered an important asset to be transferred.

The conducted analysis has brought to light distinct phases of surface depletion, unveiling a cyclic pattern of surface roughness. This pattern involves recurrent cycles of roughness increase and decrease, oscillating between the flattening of the texture and the formation of cracks, pits, and features that expose new surfaces with higher coarseness. This identified repetitive behaviour of the GSTs' surface is being documented for the first time, owing to the innovative application of a quantitative approach to an experimental collection constructed according to a sequential strategy. This offers valuable insights into the examination of archaeological GSTs, for which the use-biography and the utilisation stage are typically unknown, by providing an overview of the possible wear development over time.

Moreover, the inclusion of the ventral side of the passive tools (the surface in contact with the ground) in the examined areas yields valuable insights for differentiating between utilised and unused surfaces. It is crucial to highlight that even areas not directly involved in processing undergo transformations and display distinct wear patterns. Notably, this study marks the first instance of tracing and measuring wear development on the unused side of the experimental GSTs. However, to ensure robust comparisons, the dataset requires expansion.

The data also clearly indicate that the most substantial surface modification occurs during the transition from the unused to the used stage, which was monitored in the experiments after 30 min of use. It is evident that the processing of vegetal resources leads to a decrease in roughness. However, specific patterns for certain types of resources are identifiable, such as the opposite trend with an increase in roughness parameters when processing dry roots or a significant impact on the texture during the achenes processing.

Unprecedentedly, the analysis also explores the potential use of perishable resources, such as wood, as implements for daily activities like processing vegetal resources. The quantitative analysis highlights that despite the change of lithotype and processed resource, and consequently the different kinematics of the gesture, the contact of the stone with the wood leads to a flattening of the topography of the lithic tool.

In conclusion, it is crucial to emphasise that when utilising this technique for archaeological functional interpretation, this type of data cannot stand alone. Instead, it requires a robust foundation rooted in microscopy, traceological observations, and residue analysis. This is because specific patterns may be common to multiple resources, and a comprehensive approach involving various analytical methods enhances the accuracy of functional interpretations.

## Author contributions

Conceptualization, G.S.; Methodology, G.S., M.P.; Data curation, G.S.; Formal analysis, G.S., M.P.; Investigation, G.S.; Resources, M.P., A.L.G., A.R., G.S.; Supervision, M.P., L.L., A.L.G., A.R.; Validation, G.S., M.P.; Visualization, G.S.; Writing original draft, G.S.; Writing review and editing, M.P., G.S., L.L. All authors have read and agreed to the published version of the manuscript.

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## CRediT authorship contribution statement

**Giusi Sorrentino:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Laura Longo:** Writing – review & editing, Validation, Supervision. **Alessandro Lo Giudice:** Supervision, Resources. **Alessandro Re:** Supervision, Resources. **Marco Paggi:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Formal analysis.

## Declaration of competing interest

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

## Data availability

The data presented in this study will be available upon request from the first author.

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