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Mesolithic plant processing unveiled: Multiscale use-wear analysis of the ground stone tools from Vlasac (Serbia)

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ABSTRACT

Plants and plant-based foods played a crucial role in human evolution, and the interaction between plants and humans is a highly debated topic in archaeology. Ground stone tools are considered particularly valuable evidence due to their direct involvement in various plant processing tasks. This paper investigates the use of sandstone ground stone tools coming from the site of Vlasac in the Danube Gorges region, used in plant processing tasks, providing clues about the exploitation of vegetal resources during the Mesolithic of the region. Applying a novel approach based on the combination of qualitative and quantitative methods, including optical microscopy, 3D surface texture analysis, and spatial analysis, we explore the use of ground stone tools in plant processing at the site. Our results highlight the existence of a specific plant-food processing technology in the area of the Danube Gorges during the eight millennium cal BC, alongside the familiarity of these Mesolithic foragers with the consumption of wild plants, long before the introduction of agriculture in this region.

1. Introduction

Ground stone tools (henforth GSTs) are of primary importance in investigating activities associated with plant, animal, and mineral material exploitation for subsistence as well as for daily life practices (Adams, 2014; de Beaune, 2004; Delgado-Raack et al., 2022; Delgado-Raack and Risch, 2008; Dietrich et al., 2019; Dubreuil and Savage, 2014; Wright, 1991; de Beaune, 2000). These artefacts represent a major component of the prehistoric toolkit since the Early Stone Age ~3Mya and have been employed in a vast range of activities, including the processing of plant foods (Arroyo et al., 2020; Arroyo and de la Torre, 2018; Titton et al., 2020, 2018). As these tools are used for grinding, pounding, and pulverizing grains, seeds, nuts, and underground storage organs (henceforth USOs), GSTs allow making plant foods readily digestible, unlocking nutrients and eliminating toxins in some plant species, which would otherwise be non-edible (Alonso, 2019; Stahl, 2014). Recent studies have highlighted the importance of plant foods and their processing strategies in early prehistory. Such new interest in the study of this evidence led to a more systematic investigation of ground stone tools, underlining their relevance as indirect evidence for the role of plants in prehistoric diet and technology. For instance, the use of ground stone tools to crack nuts is recorded at the Acheulean site of Gesher Benot Ya'aqov in Israel (Goren-Inbar et al., 2002) and at the Middle Palaeolithic site of Nesher Ramla (Paixão et al., 2021a). Use-wear and residues interpreted as evidence of plant processing activities have been identified on Upper Palaeolithic ground stone tools from the Gravettian sites of Dolní Věstonice (Czech Republic), Surein I (Crimea), Bilancino, and Grotta Paglicci (Italy) (Lippi et al., 2015; Longo et al., 2022, 2021; Mariotti Lippi et al., 2023; Revedin et al., 2015, 2010). In the Mesolithic, the use of ground stone tools to work nuts, grains, and tubers has been observed at several sites across Europe, including locations in Spain, Germany, and Italy (Cristiani et al., 2021; Holst et al., 2024; Roda Gilabert et al., 2016, 2015, 2012).

In this article, we present the evidence for the use of ground stone tools recovered at the Mesolithic site of Vlasac situated in the Danube Gorges area of the north-central Balkans. Here, ground stone tools start appearing in the archaeological record in the Early Mesolithic (Antonović, 2006), if not earlier. However, it is only in the Late

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Mesolithic that these tools became an essential component of the forager toolkit as documented at various sites across the region, such as Padina, Lepenski Vir, Hajdučka Vodenica, and Vlasac (Antonović, 2006; Borić et al., 2018, 2014; Srejović, 1969).

Recent studies, including the analysis of aDNA in human dental calculus and the study of plant micro remains retrieved in human ancient plaque, along with a systematic research on botanical macro-remains, have provided strong evidence for the consumption of plant foods in this region during the Mesolithic, i.e before the introduction of agriculture (Cristiani et al., 2021; Cristiani and Borić, 2016; Filipović et al., 2020, 2017, 2010; Marinova et al., 2013). From these studies, a picture has emerged of a long-lasting tradition of plant consumption among local forgers that likely prompted the development of a specific technology for plant food processing (Cristiani and Borić, 2016; Ottoni et al., 2021).

The site of Vlasac also yielded one of the largest and best preserved records of Mesolithic GSTs within the area of the Danube Gorges, which makes it an optimal context to apply a novel multiscalar functional approach, which has so far been tested only experimentally (Cristiani and Zupancich, 2020; Zupancich and Cristiani, 2020). In this paper, we combine surface metrology and spatial analysis with the microscopic observation of use-wear to provide more details about the use of ground stone tools at Vlasac in plant food processing tasks and reveal the complex life cycles of these tools.

Integrating qualitative and quantitative techniques enables us to achieve high-resolution functional data and enables us to refine our understanding of GSTs at the site. Specifically, we show how the application of 3D surface texture analysis allows us to further explore aspects of surface modifications on ground stone tools associated with plant working. Also, we demonstrate how the application of GIS can aid in our understanding of aspects related to the handling of tools, providing relevant clues for understanding the kinematics of gestures involved in plant working. Moreover, we contribute to the debate regarding the need for comparable and reproducible use-wear data, while emphasizing the importance of a multi-level approach based on the combination of classical and quantitative techniques, which has seen a rapid development over the last decade, especially concerning non-flaked technology (Arroyo and de la Torre, 2020; Benito-Calvo et al., 2018; Caruana et al., 2014; Cristiani and Zupancich, 2020; de la Torre et al., 2013; Longo et al., 2021; Marulli et al., 2023; Paixão et al., 2021b; Proffitt et al., 2021; Sorrentino et al., 2023; Zupancich et al., 2019; Zupancich and Cristiani, 2020; Marreiros et al., 2020). Finally, while exploring the potential of our proposed multi-scalar approach, the results presented in our paper provide further evidence for the familiarity that Mesolithic hunter-gatherers had with wild plant foods in the Balkans and can directly be linked with the development of a specific technology employed for plant food processing long before the introduction of agriculture in this area.

2. Archaeological background

Vlasac is one among two dozen Mesolithic sites known from the area of the Danube Gorges, located on the southern side of the Danube River, between the southern extent of the Carpathians and the northwestern foothills of the Balkan Mountains (Fig. 1) (Borić et al., 2008, 2014; Radovanović, 1996; Srejović and Letica, 1978). Excavations at the site began during the early 1970s while more recent excavation campaigns started in 2006 and are still ongoing (Borić et al., 2008, 2014). Recent radiocarbon dates indicate that the site was occupied continuously from the Early Mesolithic, ~9500 cal BC, with more intense occupation activities dating to the Late Mesolithic at the end of the eight millennium cal BC and for the most part of the sixth millennium cal BC (~7300–5900 cal BC), when the first contacts with incoming Neolithic farmers are documented (Borić et al., 2014; Borić and Griffiths, 2015). The most recent occupation of the site, corresponding to the Early Neolithic of the area, is dated between ~5900 and 5500 cal BC (Borić et al., 2014).

The archaeobotanical record shows an environment characterized by forest trees (oaks) and shrubby plants located mostly along the riverbanks (Borić et al., 2014; Filipović et al., 2010). Faunal remains indicate

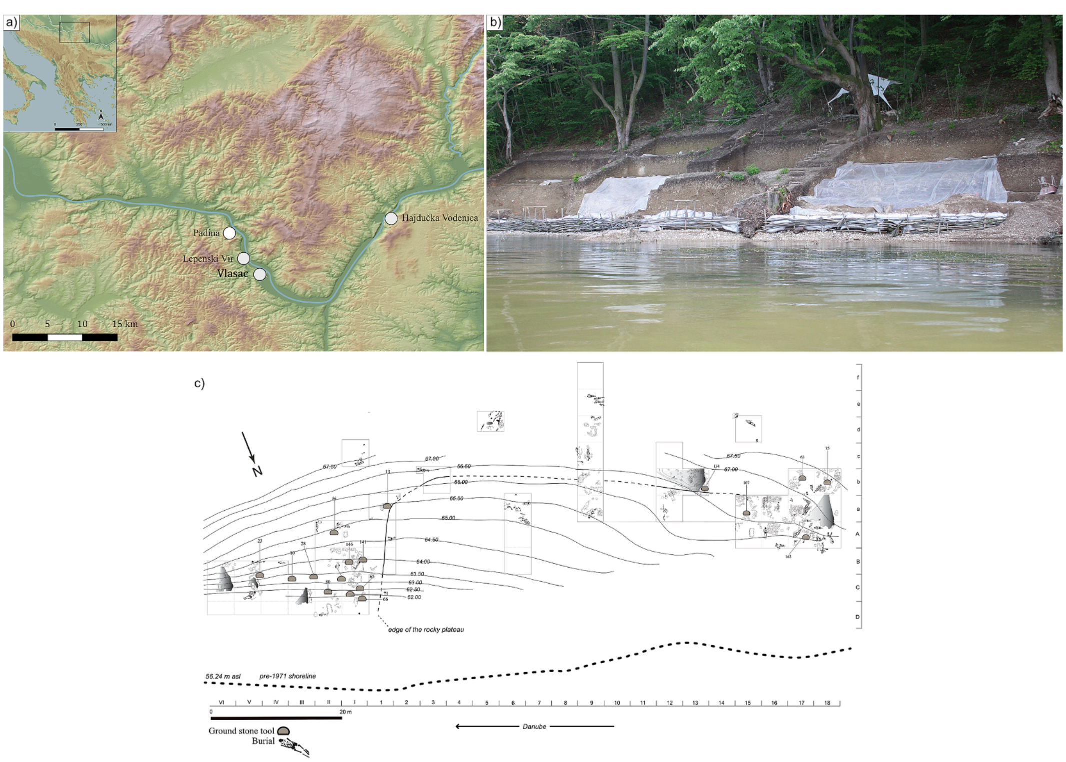

Fig. 1. a) map showing the location of Vlasac and other Mesolithic sites in the Danube Gorges area; b) view of the excavations at Vlasac in 2007 (photo credits: D. Borić); c) spatial distribution of the ground stone tools utilized in plant processing tasks.

that subsistence strategies included both hunting (e.g. red deer *Cervus elaphus*, wild boar *Sus scrofa*, aurochs *Bos primegenius*, and roe deer *Capreolus capreolus*, among the most represented game animals) and fishing of diverse species of freshwater fish (mostly catfish *Siluris glanis*, beluga *Huso huso* and other smaller species of sturgeon from the *Acipenseridae* family, and different species of the carp family *Cyprinidae* sp., among other species) (Borić et al., 2014; Cristiani and Borić, 2012; Živaljević et al., 2021). The knapped stone industry is dominated by flaked tools (e.g. flakes, scrapers and blades) made out of locally available raw materials (flint and quartz), as well as a conspicuous amount of sandstone ground stone tools (for details see below) (Borić et al., 2014). Artefacts made on hard animal materials, such as antler, bone, and teeth, are abundant and include pointed (awls, curated points) and edged tools (straight wedges) mostly produced using herbivorous long bones (primarily red deer metapodials) and antler as well as wild boar tusks. Based on the functional analysis, osseous tools were used in heavy duty and hunting tasks (Borić et al., 2014; Cristiani and Borić, 2021). At Vlasac, more than 100 burials have been found containing nearly 200 individuals comprising adults, children, and infants (Borić et al., 2008, 2014; Srejović and Letica, 1978). Of particular interest is a rich assemblage of ornaments found in association with some of the buried individuals. Beads made on modified and unmodified carp *Rutilus* sp. teeth and marine gastropods (*Tritia neritea* and *Columbella rustica*) have been found in numerous burials and are considered as evidence of a strong corporeal symbolism and group identity, testifying also to the existence of regional and long distance raw material acquisitions during the Late Mesolithic and continuing into the period of the Mesolithic-Neolithic transition (Cristiani et al., 2014; Cristiani and Borić, 2012).

Nearly 200 artefacts compose the assemblage of GSTs unearthed at Vlasac during the 1970–1971 excavation campaigns as well as during the course of the most recent fieldwork. Most of the tools are made from sandstone cobbles, but also other lithologies, such as amphibolite, aplite, mica schist, and chert, were used. Overall, the raw material is macroscopically homogeneous and characterized by grains with a high degree of angularity, densely distributed within the stone matrix and with sizes ranging between 0.2 and 1 mm. The raw material sourcing area for the sandstone boulders has been identified in the vicinity of the site, specifically in the upper reaches of the Bojetinska River (Borić et al., 2014). Based on a qualitative characterization of use-wear and residues, ground stone tools from Vlasac were used in flint knapping, bone tool manufacturing, and plant processing activities (Borić et al., 2014; Cristiani et al., 2021).

3. Materials and methods

3.1. Sample selection

The entire ground stone tool assemblage from Vlasac has been analyzed. It consists of both active and passive elements. Active tools comprise upper elements such as handstones and hammerstones, while passive tools include lower stationary elements such as grinding slabs and implements used as bases for grinding or pounding activities (Wright, 1991). All the tools have been at first observed by the naked eye as well as at a macroscopic level using a stereomicroscope at the storing facilities at the Faculty of Philosophy in Belgrade (Serbia). This first stage of analysis was aimed at a selection of specimens suitable for functional analysis that show surface modifications potentially related to use (e.g., surface flattening, localized pitting etc.). Tools affected by severe post depositional modifications (PDM), such as invasive surface concretion, high degree of fragmentation, and surface exfoliation (i.e., spalling), were excluded from further analyses, leading to a total of 44 GSTs selected for use-wear and residue analysis.

3.2. Use-wear analysis

The functional study of the ground stone tools from Vlasac is based on the combination of qualitative and quantitative analyses. The qualitative assessment of use-related surface modification was carried out by means of Optical Light Microscopy (OLM) at low and high magnifications (Keeley and Toth, 1981; Rots, 2010; Tringham et al., 1974; van Gijn, 2010; Vaughan, 1985). The analysis at low magnifications (0.7x – 120x) was performed using a ZEISS Discovery V8 and aimed at identifying use-related modifications of both the macro topography of the stone surface and the crystal grains (Adams et al., 2009; Cristiani and Zupancich, 2020; Delgado-Raack et al., 2022; Delgado-Raack and Risch, 2008; Dubreuil et al., 2023; Dubreuil and Savage, 2014; Hamon and Plisson, 2009; Hayes et al., 2018). Following Adams and colleagues (2009), surface leveling is described according to its distribution, density, incidence, morphology, and texture. Pits are described following their distribution, density orientation, depth, and shape, whereas the variables characterizing linear features include distribution, density, incidence, disposition, orientation, width, length, longitudinal and transverse morphologies. The analysis of use-related modifications on single grains comprises the description of grain extractions, fractures, leveling, edge rounding, and polishing. For the analysis of microwear (e.g., micro polish, micro striations, micro pitting), high resolution polyvinylsiloxane casts (*Hereus Provil Novo Light Fast*) of the used area(s) identified on the archaeological GSTs were molded (Banks and Kay, 2003) and observed at high magnification (100x to 500x) using a ZEISS AxioScope metallographic microscope (Dubreuil et al., 2023; Delgado-Raack et al., 2022; Cristiani and Zupancich, 2020; Hamon, 2022). Micro polish is described according to its texture, topography, incidence, density, distribution, while micro pits and micro striations are described through the same variables used at lower magnifications (see above) (Adams et al., 2009; Cristiani and Zupancich, 2020; Hamon, 2022). To assure a reliable functional interpretation, the use traces identified on the ground stone tools from Vlasac have been compared with an experimental use-wear reference collection made from sandstone pebbles collected along the banks of the Bojetinska River in 2017 and housed at the Diet and ANcient TEchnology (DANTE) Laboratory at Sapienza University of Rome. These sandstone boulders share the same characteristics of the archaeological specimens, being macroscopically homogeneous and having grains densely distributed within the matrix. The grains show a high degree of angularity and dimensions range from 0.2 to 1 mm across. The experimental reference collection includes 53 tools utilized to process vegetal and animal materials. Modern GST replicas have been used from a minimum of 240 min to a maximum of 840 min in grinding and pounding activities. Processed plant vegetal materials include wild grains, fruits, and berries, while animal substances include hide, skin, and bone.

Pictures of the identified macro wear were taken using a ZEISS Axiocam 506 high-definition colour camera, while a ZEIS Axiocam 305 high-definition color camera was used to take picture of the identified microwear.

3.3. Surface morphometrics

The quantitative assessment of use-wear focused on the analysis of surface topography. Using a ZEISS AxioZOOM v.16 motorized stereo zoom microscope equipped with a PlanNeoFluar Z 1x/0.25 (FWD 56mm) objective, 3D images of the used areas were taken at 50x. Subsequently, the images were processed using the metrological software MountainMap (v.7) by DigitalSurf. For each 3D image (2963x2377 µm), three 500x500 µm areas were extracted and processed following published protocols (Ibáñez-Estévez et al., 2021; Macdonald et al., 2019; Paixão et al., 2021b; Pedergnana et al., 2020; Pichon et al., 2023, 2021). As a first step, the image was leveled by subtraction using a Least Square Plane method and the form was removed using the Remove Form Operator (polynomial degree of 10). The latter operator is used to remove the general form intrinsic in the surface. Furthermore, a robust Gaussian filter (3x3) was applied followed by the removal of outliers (medium). Finally, 3D areal surface height parameters (ISO25178)

Table 1
3D Areal surface parameters utilized in the Analysis (ISO25178).

Parameter	Unit	Description
S_q	μm	Root mean square height
S_{sk}	–	Skewness
S_{ku}	–	Kurtosis
S_p	μm	Maximum peak height
S_v	μm	Maximum pit height
S_z	μm	Maximum height
S_a	μm	Arithmetic mean height

(Table 1) were extracted and compared with our experimental quantitative dataset computed on modern ground stone tool replicas.

3.4. Use wear spatial analysis

Use-wear spatial distribution was performed following the protocols proposed by de la Torre et al. (2013) Zupancich et al. (2019) and Zupancich and Cristiani (2020). Geographic Information System (QGis v. 3.22) was used to analyze the distribution of the utilized areas across tool surfaces and their morphological characteristics, which have proven useful in the study of ground stone tools use (Arroyo et al., 2020; Arroyo and de la Torre, 2020; Benito-Calvo et al., 2018; Caruana et al., 2014; Cristiani and Zupancich, 2020; de la Torre et al., 2013; Zupancich and Cristiani, 2020). To perform the spatial analysis of the identified traces, zenital pictures of the used surface of the tools were first georeferenced. Subsequently, the used areas identified across the tool's surface were digitized and morphometric features were computed, including the area, the distance of the used area(s) from the surface center (DfC) and the edges (DfE) of the tool as well as the amount of tool surface affected by use (PA). Statistical tests and charts were performed using R v4.1.2 (R Core Team, 2021) through RStudio 2021.09.1. The raw data and R code utilized for the statistical analyses are available on Zenodo (https://doi.org/10.5281/zenodo.13997855).

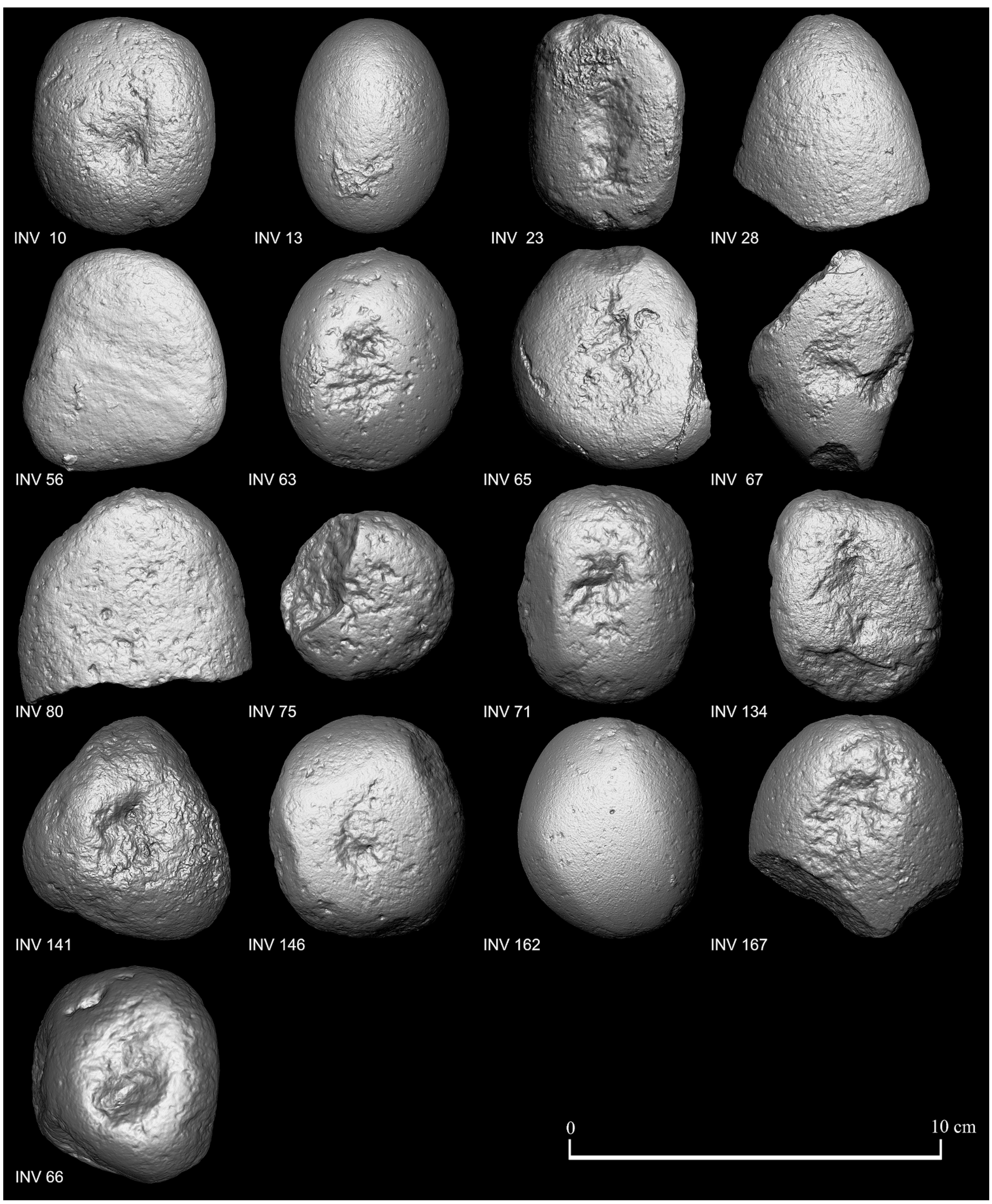

Fig. 2. The ground stone tools from Vlasac utilised in plant processing activities.

4. Results

The analyzed assemblage includes active and passive elements, the latter being the most represented category (Fig. 2). Tool shapes range from round to ovate, sub-angular, and elongated. Among the analyzed tools, 10 implements exhibit single or multiple pits, localized across one or both of their surfaces (Table 2). In most cases, the tools are well preserved with only few fractured specimens.

4.1. Plant working use-wear

At Vlasac, 38.6 % of the analyzed assemblage (i.e. 17 specimens) have been used to work vegetal materials and two use-wear patterns interpreted as the result of plant food processing have been identified (Table 3). The first use-wear patterns are represented by medium to large size leveled areas visible across the used surface of the tools. When observed at low magnifications, these areas are characterized by crystal grains with an amalgamate distribution, and leveled surfaces that in few cases show striations (Fig. 3). Under higher magnifications, medium sized polished areas are identified. Micro polish affects both the high and low topographic height of the surface and exhibits a smooth texture and a topography ranging from domed to flat. In particular, flatter topographies are identified over the higher topographic heights. Micro striations are also present within the micro polish and appear as long and narrow with mixed orientations and a polished or matte bottom. Experimentally, this combination of surface modifications and micro wear are observed on ground stone tool replicas used to process grains of wild grasses through grinding (Cristiani and Zupancich, 2020) (Fig. 4). A second use/wear pattern consists of small to medium flat spot-like areas distributed across the surface of the tool. At low magnifications, these ares exhibit distinct crystal grains characterized by lightly leveled and abraded surfaces as well as rounded edges (Fig. 3). Under high magnifications, small to medium spots of micro polish are visible. Micro polish affects both the high and low topographic heights. The texture of the micro polish is smooth while its topography is domed. Linear features have not been observed. In our experimental trials, we observed similar use-wear patterns on replicas used to process fleshy fruits. By combining the analysis of macro and micro wear with the one of plant micro particles extracted from the surface of the tools, it was possible to narrow the range of processed plants to specific grass grains (e.g. *Aegilops ventricosa*, *Bromus hordeaceus)*, nuts (e.g. *Corylus avellana*), and berries (e.g. *Cornus mas*) (Cristiani et al., 2021) (Figs. 3, 4).

4.2. Pits

A further use pattern identified among the analyzed GSTs is represented by pits. On more than a half (58.8 %) of the tools bearing use-wear associated with plant processing tasks, single or multiple pits have been identified. The latter occur on one or on both surfaces of the tool and their shapes vary from elongate to round or irregular. When

Table 2

Vlasac ground stone tools used in plant working activities. Sq. = Square; Sh. = shape; Pi. = pits; N. Pi. = number of pits; Pi. Loc. = location of pit(s); Pi. Sh. = pit shape; L. = length; W. = width; Th. = thickness; We. = weight; V. = volume; Rel. area = relative area; Rel. thickness = relative thickness; Pres. = state of preservation.

ID	Sq.	Too type	Sh.	Pi.	N. Pi.	Pi. Loc.	Pi. Sh.	L. (cm)	W. (cm)	Th. (cm)	We. (gr)	V. (cm3)	Rel. area	Rel. thickness	Pres.
10	F KB 0 1/III	Handstone – Grinder	Subangular	Y	2	Both surfaces	Round	12.7	10.5	7.88	1542	645	11.55	0.071	Preserved
13	a1-VIII	Handstone – Grinder	Round	N	0	Absent	Absent	11	8.16	5.68	680	287	9.47	0.091	Preserved
23	BV/C/ IV-X	Indeterminable	Subangular	Y	3	Both surfaces	Elongated	11.7	8.79	8.76	823	367	10.14	0.103	Preserved
28	BIII-C/V	Passive base	Ovate	N	0	Absent	Absent	13.3	12	7.35	1283	499	12.63	0.076	Fractured
56	A/II-XIII	Passive base	Round	N	0	Absent	Absent	15.9	14.8	7.7	1038	368	15.34	0.086	Preserved
63	b/17-XV	Handstone – Grinder	Round	N	0	Absent	Absent	8.4	6.6	4.47	403	141	7.45	0.105	Preserved
65	C/I-VI	Passive base	Round	Y	2	One surface	Elongated	9.98	8.43	5.55	680	298	9.17	0.090	Fractured
66	C/I II/V	Indeterminable	Round	Y	2	Both surfaces	Round	9.5	8.5	7.6	1170	437	8.99	0.0806	Preserved
67	C/I-C/ II-III	Passive base	Subangular	Y	1	One surface	Round	10.8	8.4	5.91	633	253	9.52	0.097	Fractured
71	C/I-V	Handstone – Grinder	Round	Y	1	One surface	Elongated	7.33	5.79	4.59	309	119	6.51	0.122	Preserved
75	b/18-V	Handstone – Grinder	Subangular	N	0	Absent	Absent	5.53	5.29	3.45	137	57	5.41	0.159	Fractured
80	C/II-II/ 6	Passive base	Ovate	N	1	One surface	Irregular	9.85	8.35	3.72	547	225	9.07	0.082	Fractured
134	b/V3-XII	Iindeterminable	Subangular	Y	2	Both surfaces	Round	12.2	9.57	8.13	1433	565	10.81	0.075	Preserved
141	B/I 0–8.9	Handstone – Grinder	Round	Y	2	Both surfaces	Elongated	10.8	9.92	9.22	1149	476	10.35	0.090	Preserved
146	B/I-ISPOD 1.9	Handstone – Grinder	Round	Y	1	One surface	Round	6.65	5.7	4.66	275	106	6.16	0.130	Preserved
162	A/16-X	Handstone – Grinder	Round	N	0	Absent	Absent	10.6	9.3	7.52	1143	424	9.93	0.081	Preserved
167	a/15-VII	Indeterminable	Round	Y	1	One surface	Elongated	8.94	8.82	5.65	611	241	8.88	0.096	Fractured

Table 3
Description of the use-wear identified on the ground stone tools from Vlasac and interpret as a result of plant processing activities.

ID	Tool	State of preservation	PDM	Micro polish distribution and density	Micro polish incidence	Micro polish texture	Micro polish topography	Micro striation description	Micro striation orientation	Cristal grain modification	Gesture
10	Handstone – Grinder	Preserved	Light soil concretion	Loose closed	High topographic heights	Smooth	Domed	Short narrow with polished bottom	Unidirectional	Y	Longitudinal back and forth
13	Handstone – Grinder	Preserved	None	Loose closed	High and low topographic heights	Smooth	Domed and flat	Short deep with matt bottom	Mixed	N	Longitudinal mixed
23	Indeterminable	Preserved	Light soil concretion	Loose connected	High and low topographic heights	Rough tending to smooth	Domed and flat	NA	NA	N	Longitudinal unidirectional
28	Passive base	Fractured	None	Loose closed	High and low topographic heights	Smooth	Domed	NA	NA	Y	Longitudinal unidirectional
56	Passive base	Preserved	Heavy surface concretion on one surface	Covered close	High and low topographic heights	Smooth	Domed and flat	NA	NA	Y	Mixed
63	Handstone – Grinder	Preserved	Light surface abrasion	Loose closed	High topographic heights	Smooth	Domed and flat	NA	NA	N	Longitudinal
65	Passsive base	Broken	Fractures	Covered connected	High and low topographic heights	Smooth	Domed and flat	Short narrow with a matt bottom	Mixed	N	Longitudinal mixed
66	Indeterminable	Preserved	None	Loose closed	High and low topographic heights	Smooth	Domed and cratered	NA	NA	Y	Mixed
67	Passive base	Broken	Light soil concretion and surface abrasion	Covered close	High and low topographic heights	Smooth	Domed	Short deep with matt bottom	Unidirectional	N	Longitudinal unidirectional
71	Handstone – Grinder	Preserved	None	Covered close	High and low topographic heights	Smooth	Domed and flat	Long shallow with polished bottom	Mixed	Y	Longitudinal mixed
75	Handstone – Grinder	Broken	Fractures	Loose closed	High topographic heights	Rough tending to smooth	Domed	Short narrow with a polished bottom	Unidirectional	N	Longitudinal unidirectional
80	Passive base	Broken	None	Covered close	High and low topographic heights	Smooth	Domed and flat	Short narrow with matt bottom	Unidirectional	Y	Longitudinal unidirectional
134	Indeterminable	Preserved	None	Lose close	High and low topographic heights	Smooth	Domed	Short deep with a matt bottom	Unidirectional	Y	Longitudinal unidirectional
141	Handstone – Grinder	Preserved	Soil concretion	Covered close	High topographic heights	Smooth	Domed and flat	NA	NA	Y	Longitudinal
146	Handstone – Grinder	Preserved	Light soil concretion	Covered close	High topographic heights	Rough tending to smooth	Domed	Short narrow with a matt bottom	Unidirectional	N	Longitudinal unidirectional
162	Handstone – Grinder	Preserved	None	Covered close	High and low topographic heights	Smooth	Domed	Short narrow with a matt bottom	Unidirectional	Y	Longitudinal unidirectional
167	Indeterminable	Broken	Light surface abrasion	Concentrated close	High and low topographic heights	Rough	Granula and domed	NA	NA	Y	Perpendicular

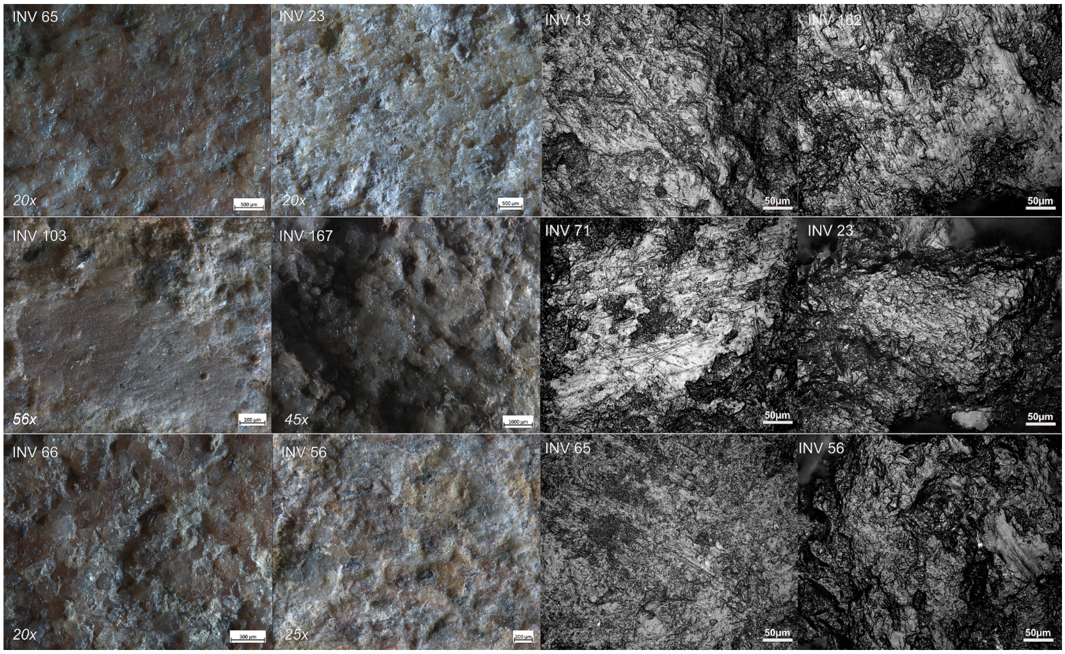

Fig. 3. Surface modification and micro polishes identified on the ground stone tools of Vlasac and attributed to the use of the tools in processing wild grains and fleshy fruits. Micro polish pictures are all taken at 500x of magnification.

analyzing the morphology of the tools bearing pits across their surfaces, we notice that their number is positively correlated with the weight (Spearman rank correlation *R = 0.74, p-value = 0.014*) and with the tool's relative area (Spearman rank correlation *R = 0.66, p-value = 0.037*), possibly indicating that larger and heavier specimens were potentially involved in heavier duty tasks and most likely not associated with the working of plants.

Unfortunately, the presence of concretions hindered the possibility to analyze possible use-related modifications affecting the surface and grains of the pits, which could provide further clues about their origin. However, a comparison of the morphologies of the pits observed on the ground stone tools of Vlasac with those developed experimentally and observed archaeologically (Arroyo and de la Torre, 2018; Pardoe et al., 2019; Roda Gilabert et al., 2015) leads us to assume that the identified pits are most likely related to the use of these ground stones in bipolar knapping. Furthermore, the hypothesis that the pits might not have been linked to the use of the tools in working plants is also supported by the analysis of the spatial distribution and morphometry of the used areas across the ground stone tool surfaces. Indeed, the surface areas where plant working traces are identified are only seldomly spatially related to the pits.

4.3. Use-wear spatial distribution

Overall, surface modifications associated with plant working are limited across the surface ($\bar{x}$ PA 6.61 %) and have a small extent ($\bar{x}$ area 41.3 mm^2) (Table 4). Moreover, significant differences are observed neither in the occurrence (PA) (Kruskal-Wallis chi-squared = 4, df = 2, p-value = 0.7) nor in the dimension (area) (Kruskal-Wallis chi-squared = 0.1, df = 2, p-value = 0.6) of the used areas within active, passive, or indeterminate tools (Fig. 5).

The spatial distribution of the used areas shows that they are mostly localized near the edges of the surface (Fig. 5 Fig. 6b, c; Table 2). When compared by tool types, utilized areas are closer to the edges in active ($\bar{x}$ DfE 23.4 mm) than in passive ($\bar{x}$ DfE 29.8 mm) tools (Kruskall – Wallis test chi-squared = 14, df = 1, p-value = <0.001) (Fig. 6c). Taking into account dimensions of the tool, this evidence provides insightful clues about the possible handling of active tools during their use and, consequently, sheds light on the grinding technique that was adopted. In particular, the location of the used area(s) near the edge of the surface indicates that, while used, the object was positioned perpendicularly and with a certain degree of inclination to the surface of the passive tool (Fig. 6d). During our experimental trials, we found this handling method highly suitable when processing small quantities of materials using short back and forth grinding gestures.

4.4. 3D surface texture analysis

The analysis of the used areas at low and high magnification and the comparison with the wear developed on experimental replicas used to work plants allowed us to assume the use of ground stone tools from Vlasac to work grains, fruits, and berries (Cristiani et al., 2021). This interpretation, based on the qualitative characteristics of the identified traces, is further supported by the 3D surface texture analysis of the used areas. Experimentally, we observed that five out of the seven measured 3D aerial surface parameters show significant differences between plant working and animal substance processing. Specifically, the used area of the ground stone tool replicas utilized in plant processing tasks show significantly lower values in the overall mean surface roughness (*Sa*), the maximum height of surface peaks (*Sp*), the standard deviation of the height distributions (*Sq*), the Skewness of the height distribution (*Ssk*), and the maximum height of pits (*Sv*), indicating a more homogeneous surface topography when compared to the one resulting from the working of animal matter or to the unused sandstone surfaces.

Measuring the same set of 3D aerial surface parameters across the used areas of ground stone tools from Vlasac no significant differences have been observed with the values documented on the experimental replicas utilized in plant working activities, suggesting a similar homogeneous surface topography (Fig. 7a-c, Table 5). Theses results are in agreement with the observations made about the archaeological ground stone tools' surfaces using low magnifications, where the used areas show an overall flattening of the stone surface, with contiguous grains and with a moderate leveling of their surfaces and rounding of their edges (Fig. 3). Conversely, significant differences are observed when a comparison is made with the ones measured on the experimental replicas used to work animal substances (soft and hard) and the unused

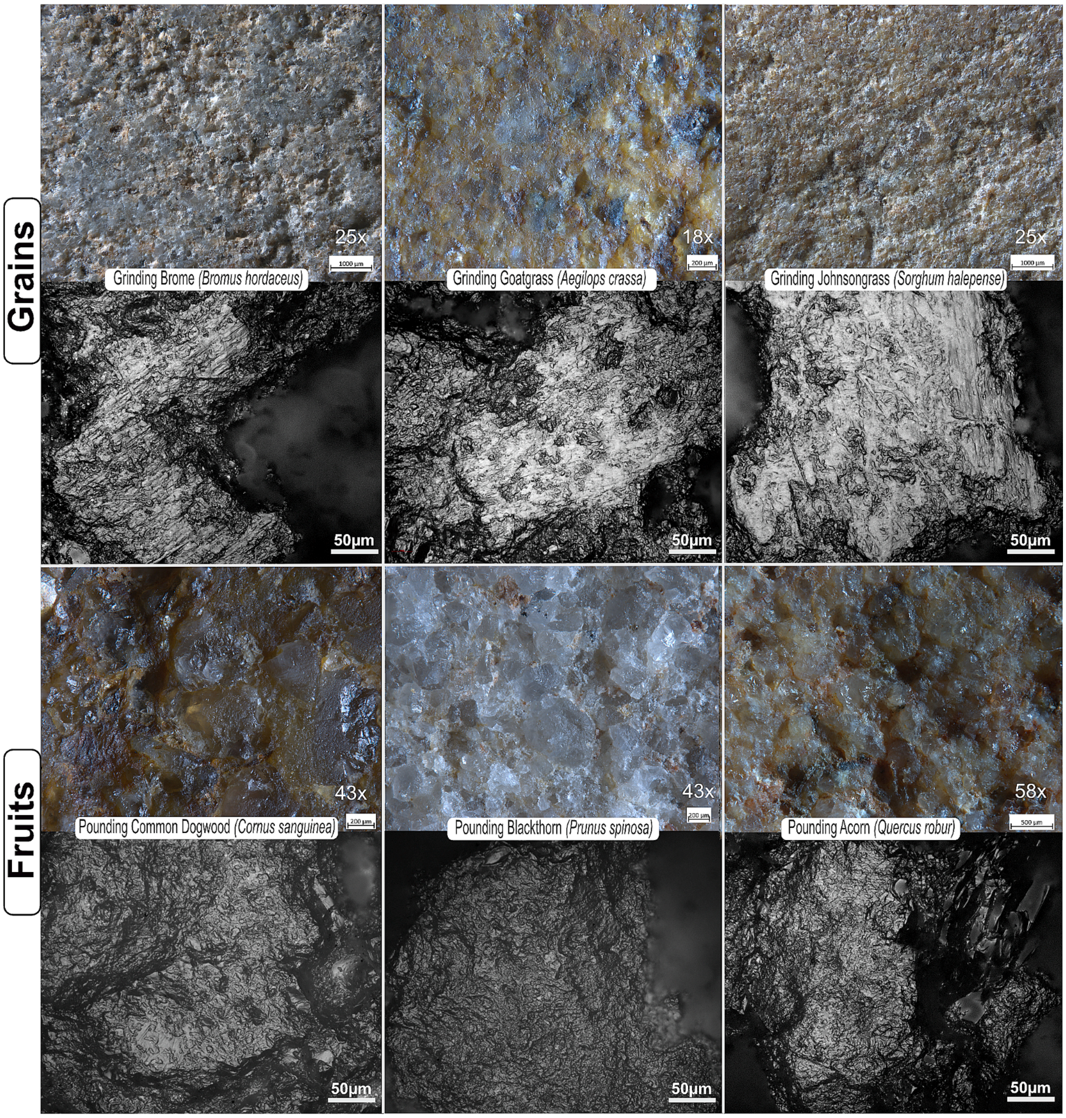

Fig. 4. Experimental reference of use wear associated with the working of wild grass grains and fleshy fruits. Micro polish picture are all taken at 500x of magnification.

Table 4
A summary statistics of the spatial distribution of used areas. DfC = distance from surface center; DfE = distance from surface edge, PA = surface affected by use. Measurements of the used surface areas are normalized for the area of the active surface.

ID	Min.Area (mm^2)	Max. Area (mm^2)	Mean Area (mm^2)	SD Area (mm^2)	Min.DfC (mm)	Max. DfC (mm)	Mean DfC (mm)	SD DfC (mm)	Min. DfE (mm)	Max. DfE (mm)	Mean DfE (mm)	SD DfE (mm)	PA (%)
10	21.79	240.93	95.62	125.85	25.62	49.7	33.67	13.90	2.37	47.38	27.281	22.89	2.49
13	50.75	96.75	75.19	24.88	16.40	20.9	19.11	2.06	30.38	37.54	32.798	3.24	4.14
23	4.00	135.75	36.36	42.86	13.01	29.6	18.32	5.92	23.37	42.28	33.832	6.71	4.39
28	2.25	442.25	129.69	138.20	4.28	37.0	19.64	10.88	17.12	56.65	39.365	12.11	14.37
56	0.25	385.50	43.21	73.51	14.14	63.4	34.84	13.90	11.87	70.08	41.470	15.35	0.79
63	1.75	60.00	13.96	16.63	12.23	21.3	16.25	2.74	18.27	26.71	22.233	2.98	3.65
65	3.50	48.75	19.69	14.34	5.05	38.1	22.58	10.53	10.07	39.91	22.702	8.55	2.7
66	0.03	6.65	2.42	2.66	1.14	33.5	21.93	12.84	17.79	42.91	25.570	10.30	0.17
67	0.50	118.25	23.30	37.20	6.71	32.6	17.05	8.84	0.01	0.04	0.027	0.01	4.92
71	0.75	38.75	14.97	15.20	11.95	28.3	15.52	5.26	3.07	24.92	19.054	6.98	7.63
75	2.25	82.75	41.25	40.41	5.77	11.5	8.87	2.50	15.78	20.48	17.672	2.29	7.15
80	4.50	153.00	36.13	39.96	7.66	39.9	18.57	7.81	5.81	42.63	26.397	9.59	7.29
134	1.50	106.25	35.46	32.91	7.62	42.5	24.38	9.68	7.35	53.42	32.135	12.15	7.85
141	0.25	82.00	33.67	32.47	17.41	42.3	23.52	7.15	5.34	33.35	27.074	8.00	4.12
146	6.75	82.25	31.75	34.63	10.94	22.3	16.50	5.26	10.29	18.76	15.320	3.88	39.91
162	9.00	234.50	80.00	88.49	20.52	28.2	24.62	3.12	21.47	31.56	26.554	3.70	4.87
167	1.75	61.00	18.57	21.63	13.55	24.2	19.27	4.02	21.94	31.39	25.931	3.83	2.14

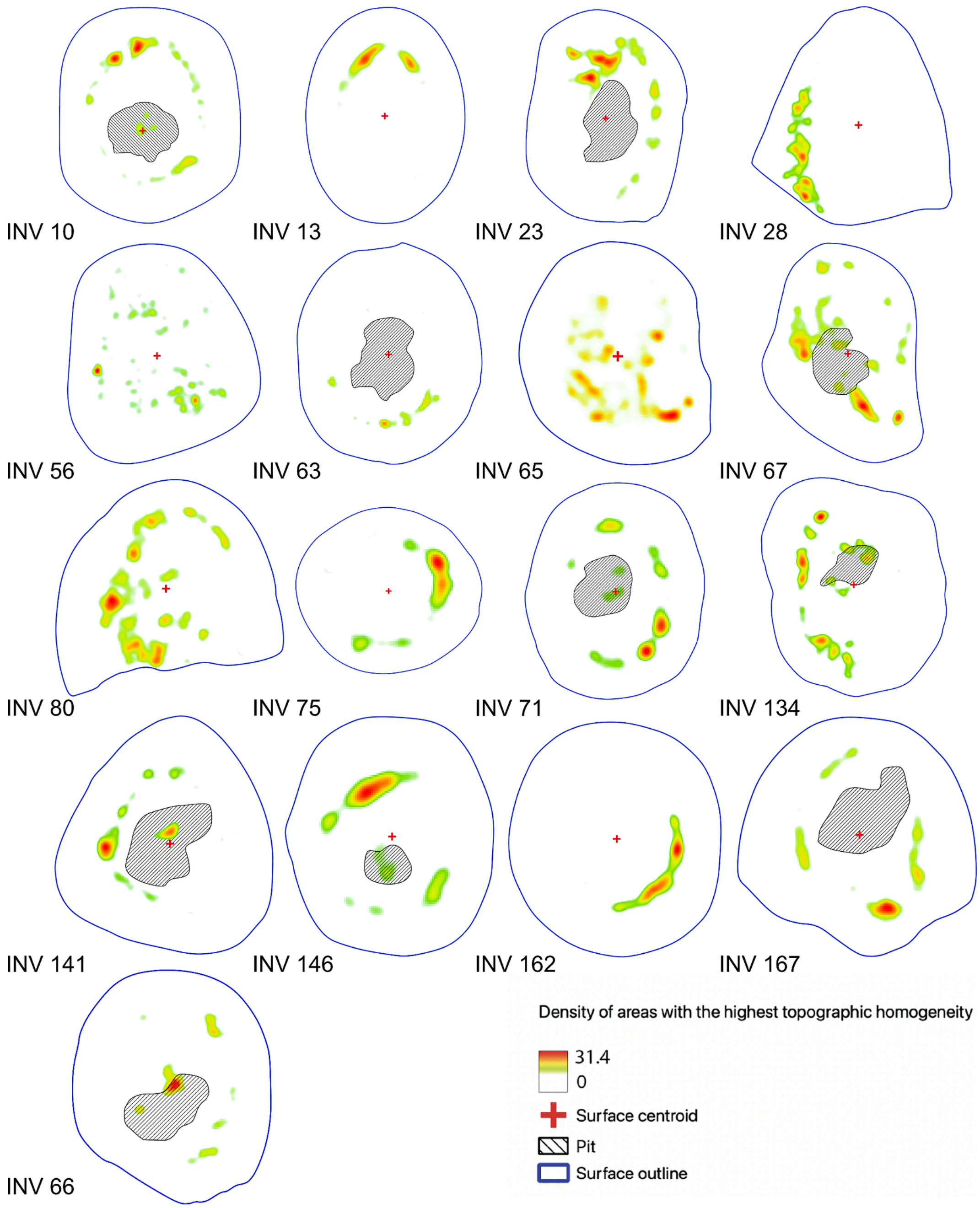

Fig. 5. Spatial distribution of surface modifications identified on the analyzed tools.

natural sandstone surfaces (Table 5), which instead, when observed at low magnification exhibit a more heterogenous surface topographic (Cristiani and Zupancich 2020).

5. Discussion

Prehistoric foragers relied significantly on wild plants before the advent of agriculture and plant domestication (Cristiani et al., 2021; Hardy and Martens, 2016; Kabukcu et al., 2022; Zvelebil, 1994). The role of plant foods has recently been assessed in the central Balkans, where a rich repertoire of non-flaked stone technology for plant processing suggests grass grains, seeds, and fruits were regularly consumed already ~9500 years cal BC (Cristiani et al., 2021, 2016; Filipović et al., 2010; Ottoni et al., 2021). In this paper, we provide further evidence through a novel combination of qualitative and quantitative techniques in the study of ground stone tools. In particular, the analysis of 3D aerial surface parameters and use-wear spatial distribution coupled with the optical observation of traces at low and high magnifications allowed us to evaluate systematically the surface modification observed on the ground stone tools of Vlasac. Accordingly, the functional interpretation is not solely based upon the resemblance of the descriptive feature of macro and micro wear but is further strengthened by statistically testable and reproducible data.

On a methodological level, our results are relevant as they show how surface morphometrics applied at low magnification represent a valuable means of studying use-wear, particularly in the case of ground stone tools. To date, most published research demonstrates the reliability of surface quantification at high magnifications (e.g. > 50x), focusing on the measurements of surface parameters of use-related micro polish (Chondrou et al., 2021; Ibáñez-Estévez et al., 2021; Macdonald et al.,

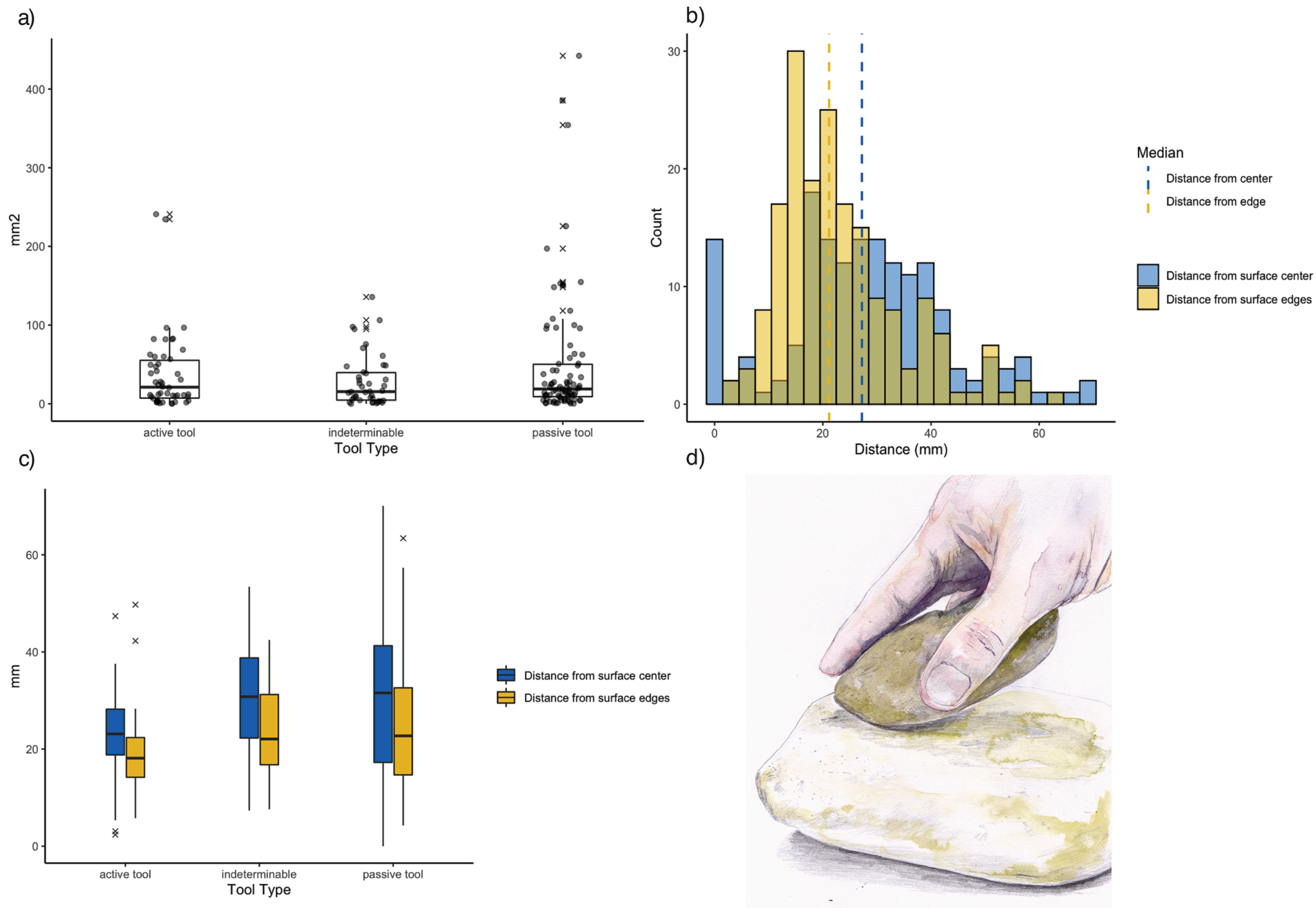

Fig. 6. Analysis of use-wear morphometrics and spatial distribution across the tools' surface. a) box and whisker plot of the area of the identified used areas; b) histogram of the distances between the used areas and the surface center and edge; c) box and whisker plot of the distance between the used areas and the surface center and edge per tool typology; d) suggested handling mode of the active tools (Drawing T. Pichon).

2019; Paixão et al., 2021b, 2021a; Pichon et al., 2023, 2021). Our study successfully shows how the quantification of surface topography at low magnifications (<=50x) throughout the analysis of areal 3D surface parameters can help us in providing reliable and functional interpretations of ground stone tools. In this sense, we offer the first attempt to discriminate between worked materials, considering a limited set of variables. A future implementation of other surface parameters already found reliable in the quantification of use-wear on flaked stone tools (Ibáñez and Mazzucco, 2021; Ibáñez-Estévez et al., 2021; Pichon et al., 2023) would allow us to enhance the interpretative potential of quantitative surface data acquired at low magnifications. Furthermore, the distribution of the used areas allowed us to speculate about the handling of the tools during their use. Specifically, the localisation of the used areas near the edges of the surface suggests that the tools were used most likely perpendicularly rather than flat on the worked material, a handling mode that favours performing short and punctual gestures. These results are confirmed experimentally as such a gripping setup has proven efficient in the grinding of cereals performed through short longitudinal and circular motions (Dietrich, 2021; Dietrich et al., 2019). Given these evidence we suggest that at Vlasac, the coarse flour obtained by grinding grass grains using ground stone tools was probably consumed in the form of porridge-like product (Dietrich et al., 2020; Dietrich and Haibt, 2020; Eitam et al., 2015; González Carretero et al., 2017; Haaland, 2007), an interpretation which finds support also in the limited extension of the used areas most likely resulting from a rough processing of plant materials. A further evidence supporting this hypothesis comes from the frequent presence of grit particles within the dental calculus matrix of the individuals buried at the site (Cristiani et al., 2021).

Besides investigating the use of ground stone tools in plant working, we have also been able to gather data on the assemblage composition and life cycles of these tools at Vlasac. As suggested by a techno-morphological analysis, in several cases we have been able to recognize stages of re-use or recycling. Overall, among the artefacts utilized in plant processing the number of "unambiguous" passive elements is limited. This pattern can be explained by the fact that potentially large stationary elements, like the ones recovered at Duvensee, Friesack, and Rothenklempenow in Germany (Holst, 2021; Holst et al., 2024), were used as passive bases and have not been recorded at the site during excavations due to their limited archaeological visibility, i.e., the absence of technological modifications (Roda Gilabert et al., 2016, 2012). Also, the low number of passive bases might be explained by the fact that these may have been made of perishable material. In this sense, of relevance is ethnographic evidence on the use of bases made of wood bark during the processing of cereals in north Africa (Peña-Chocarro et al., 2005). This assumption, however, will need further experimental trials in order to identify specific macro and microwear associated with the use of passive bases made of perishable materials such as wood or bark. A further characteristic of the ground stone tools from Vlasac is the frequent presence of pits over the surfaces of the tools, which indicate their re-use and/or recycling over time along with hinting towards their multipurpose nature. Single or multiple pits identified on the surfaces of specimens used in plant working as active elements indicate that most likely these were re-used, possibly also as passive bases, for heavy duty

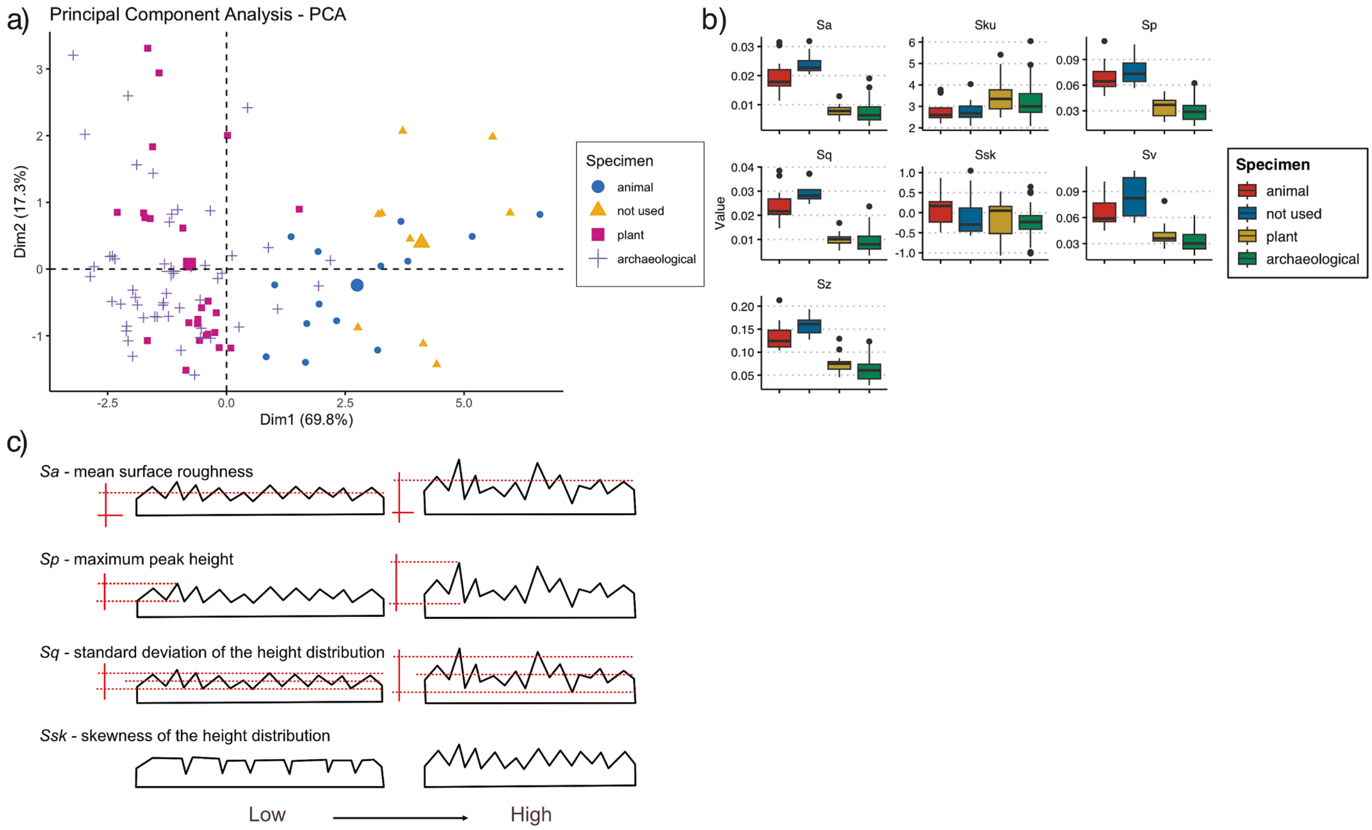

Fig. 7. Comparison of the aerial surface parameters (ISO27178) computed on the experimental replicas and on the used areas of the ground stone tools from Vlasac. a) Principal Component Analysis of the experimental and archaeological aerial surface parameters; b) boxplot of the experimental and archaeological aerial surface parameters; c) visual representation of some of the analyzed surface parameters (modified from Ackermans et al., 2021).

tasks. Pit morphologies are most likely linked to bipolar knapping (Arroyo and de la Torre, 2020) rather than to nut cracking (Holst, 2021; Pardoe et al., 2019). In support of this functional interpretation is the flaked stone tool assemblage from Vlasac, where the production of flaked tools through bipolar knapping is well attested (Borić et al., 2014; Kozłowski and Kozłowski, 1982). A further instance of the use of ground stone tools as bases for bipolar knapping comes from the Mesolithic site of Font de la Ros in Spain (Roda Gilabert et al., 2015, 2012).

Other than bipolar knapping, the pits affecting the surfaces of the ground stone tools from Vlasac indicate their probable involvement in craft activities such as bone working. Indeed, the shape of the pits also resembles the depressions formed on the experimental replicas used to produce bone blanks from metapodials. In this case, a ground stone tool is used as a hammerstone to strike a flint wedge, splitting the bone in half to obtain suitable blanks that can be worked later through scraping and/or polishing (Borić et al., 2021; Cristiani and Borić, 2021; d'Errico et al., 2003; Vitezović, 2013). Unfortunately, the presence of concretions inside the pits prevents the identification of any macro or microwear to be compared with our experimental references, which might further support this assumption. Moreover, no elements indicating the sequence of their use emerges from the analysis of wear distribution across the surface of the ground stone tools at Vlasac. Specifically, we did not observe any clear overlapping of traces (i.e., pits developing within flat surfaces), which might allow us to infer that the ground stone tools were involved in bipolar knapping or bone tool production activities as the final stage of their use.

However, the involvement of ground stone tools in a wide range of activities underlines complex and long life histories of these objects and their use in both dietary and non-dietary practices (i.e., bone and flint tool production). It demonstrates the role they played in the lifeways of Mesolithic hunter-gatherers at the site. The reuse and recycling of the ground stone tools used in plant working confirms the definition of such tools as part of an incipient plant food technology, which still did not acquire its task-specific character. It will emerge later in the Neolithic. Yet, ground stone tools were surely becoming an essential component of Late Mesolithic forager toolkit during the Early Holocene.

6. Conclusions

In the Danube Gorges, ground stone tools became a key component of the stone assemblage in the Late Mesolithic. They played an important role in daily activities of hunter-gatherer communities of the region. Ground stone tools are involved in various aspects of prehistoric lifeways, including dietary and non-dietary practices (i.e. craft). In this paper, we explored the use of ground stone tools in plant processing tasks at Vlasac. Through the combination of qualitative and quantitative methods of use-wear analysis, including optical microscopy, 3D surface texture analysis, and spatial analysis, we provide evidence for the use of ground stone tools to process wild grass grains as well as fruits available in the site's environs. The functional evidence gathered from the study of ground stone tools at Vlasac is in agreement with the data obtained from the analysis of dental calculus of individuals buried at the site. Our work supports the claim about the primary role of plants in dietary habits of Mesolithic hunter-gatherers and provides further evidence for their extensive knowledge of and familiarity with a diverse range of plant resources available in the region during the Early Holocene. Furthermore, our insights about the use of ground stone tools in processing plant foods point to the emergence of an incipient plant food technology during the Late Mesolithic in the area as an essential component of the Early Holocene forager toolkit.

Table 5
Pairwise comparison (Wilcoxon rank sum test) of aerial surface parameters recorded on the ground stone tools from Vlasac, the experimental replicas used in plant and animal working, and the natural sandstone (p-value adjustment Bonferroni).

Surface parameter	Archaeological sample	Experimental sample	p-value	Significance
Sa	Vlasac GSTs	Experimental animal matter	<0.0001	****
		Unused sandstone	<0.0001	****
		Experimental plant material	0.372	ns
Sku	Vlasac GSTs	Experimental animal matter	0.053	ns
		Unused sandstone	0.246	ns
		Experimental plant material	0.226	ns
Sp	Vlasac GSTs	Experimental animal matter	<0.0001	****
		Unused sandstone	<0.001	****
		Experimental plant material	0.052	ns
Sq	Vlasac GSTs	Experimental animal matter	<0.001	****
		Unused sandstone	<0.001	****
		Experimental plant material	0.25	ns
Ssk	Vlasac GSTs	Experimental animal matter	1	ns
		Unused sandstone	0.268	ns
		Experimental plant material	1	ns
Sv	Vlasac GSTs	Experimental animal matter	<0.001	****
		Unused sandstone	<0.001	****
		Experimental plant material	0.118	ns
Sz	Vlasac GSTs	Experimental animal matter	<0.001	****
		Unused sandstone	<0.001	****
		Experimental plant material	0.028	*

CRediT authorship contribution statement

Andrea Zupancich: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Emanuela Cristiani:** Writing – original draft, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Marialetizia Carra:** Writing – original draft. **Dragana Antonović:** Writing – original draft. **Dušan Borić:** Writing – original draft, Investigation, Conceptualization.

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.

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Data availability

Link to a Zenodo repository has been added to the text

References

Ackermans, N.L., Winkler, D.E., Schulz-Kornas, E., Kaiser, T.M., Martin, L.F., Hatt, J.-M., Clauss, M., 2021. Dental wear proxy correlation in a long-term feeding experiment on sheep (Ovis aries). J. r. Soc. Interface 18, 20210139.
Adams, J.L., 2014. Ground stone analysis: A technological approach. University of Utah Press, Salt Lake City, UT.
Adams, J.L., Delgado, S., Dubreuil, L., Hamon, C., Plisson, H., Risch, R., 2009. Functional analysis of macro-lithic artefacts: A focus on Working Surfaces, in: Sternke, F., Eigeland, L., Costa, L.-J. (Eds.), BAR International Series. Presented at the Non-Flint Raw Material Use in Prehistory, Archaeopress.
Alonso, N., 2019. A first approach to women, tools and operational sequences in traditional manual cereal grinding. Archaeol. Anthropol. Sci. 11, 4307–4324.
Antonović, D., 2006. Stone tools from Lepenski Vir. Institute of Archaeology Knez Mihailova 35, Belgrade Serbia & Montenegro.
Arroyo, A., de la Torre, I., 2018. Pounding tools in HWK EE and EF-HR (Olduvai Gorge, Tanzania): Percussive activities in the Oldowan-Acheulean transition. J. Hum. Evol. 120, 402–421.
Arroyo, A., de la Torre, I., 2020. Pitted stones in the Acheulean from Olduvai Gorge Beds III and IV (Tanzania): A use-wear and 3D approach. J. Hum. Evol. 145, 102837.
Arroyo, A., Harmand, S., Roche, H., Taylor, N., 2020. Searching for hidden activities: Percussive tools from the Oldowan and Acheulean of West Turkana, Kenya (2.3–1.76 Ma). J. Archaeol. Sci. 123, 105238.
Banks, W.E., Kay, M., 2003. High Resolution Casts for Lithic Use-Wear Analysis. Lithic Technol. 28.
Benito-Calvo, A., Arroyo, A., Sánchez-Romero, L., Pante, M., de la Torre, I., 2018. Quantifying 3D Micro-Surface Changes on Experimental Stones Used to Break Bones and Their Implications for the Analysis of Early Stone Age Pounding Tools. Archaeometry 60, 419–436.
Borić, D., Cristiani, E., Pravidur, A., Marić, A., Whallon, R., 2021. Osseous tools and personal ornaments from the Epigravettian sequence at Badanj. Herald of the National Museum of Bosnia and Herzegovina in Sarajevo n.s. – A. Archaeology 55, 7–72. https://doi.org/10.21203/rs.3.rs-209080/v1.
Borić, D., Griffiths, S., 2015. The living and the dead, memory and transition: Bayesian modelling of Mesolithic and neolithic deposits from vlasac, the Danube gorges: The living and the dead, memory and transition. Oxf. J. Archaeol. 34, 343–364.
Borić, D., French, C., Dimitrijević, V., 2008. Vlasac revisited: formation processes, stratigraphy and dating. Documenta Praehistorica 35, 261–287.
Borić, D., French, C.A.I., Stefanović, S., Dimitrijević, V., Cristiani, E., Gurova, M., Antonović, D., Allué, E., Filipović, D., 2014. Late Mesolithic lifeways and deathways at Vlasac (Serbia). J. Field Archaeol. 39, 4–31.
Borić, D., Higham, T., Cristiani, E., Dimitrijević, V., Nehlich, O., Griffiths, S., Alexander, C., Mihailović, B., Filipović, D., Allué, E., Buckley, M., 2018. High-Resolution AMS Dating of Architecture, Boulder Artworks and the Transition to Farming at Lepenski Vir. Sci. Rep. 8, 14221.
Caruana, M.V., Carvalho, S., Braun, D.R., Presnyakova, D., Haslam, M., Archer, W., Bobe, R., Harris, J.W.K., 2014. Quantifying traces of tool use: A novel morphometric analysis of damage patterns on percussive tools. PLoS One 9, 1–18.
Chondrou, D., Bofill, M., Procopiou, H., Vargiolu, R., Zahouani, H., Valamoti, S.M., 2021. How do you like your cereal? A qualitative and quantitative use-wear analysis on archaeological grinding tools from prehistoric Greek sites. Wear 203636.
Cristiani, E., Borić, D., 2021. Technology of osseous artefacts in theMesolithic Danube Gorges: The evidence fromVlasac (Serbia), in: Borić, Dušan, Antonović, D., Mihailović, B. (Eds.), Foraging Assemblages Volume 2. Serbian Archaeological Society, Belgrade, Republic od SerbiaThe Italian Academy for Advanced Studies in America, Columbia University, New York, USA.
Cristiani, E., Borić, D., 2012. 8500-year-old Late Mesolithic garment embroidery from Vlasac (Serbia): Technological, use-wear and residue analyses. J. Archaeol. Sci. 39, 3450–3469.
Cristiani, E., Borić, D., 2016. Mesolithic harpoons from Odmut, Montenegro: Chronological, contextual, and techno-functional analyses. Quat. Int. 423, 166–192.
Cristiani, E., Živaljević, I., Borić, D., 2014. Residue analysis and ornament suspension techniques in prehistory: cyprinid pharyngeal teeth beads from Late Mesolithic burials at Vlasac (Serbia). J. Archaeol. Sci. 46, 292–310.
Cristiani, E., Radini, A., Edinborough, M., Borić, D., 2016. Dental calculus reveals Mesolithic foragers in the Balkans consumed domesticated plant foods. Proc. Natl. Acad. Sci. 113, 10298–10303.
Cristiani, E., Zupancich, A., 2020. Sandstone Ground Stone Technology: a Multi-level Use Wear and Residue Approach to Investigate the Function of Pounding and Grinding Tools. J. Archaeol. Method Theory. https://doi.org/10.1007/s10816-020-09488-1.
Cristiani, E., Radini, A., Zupancich, A., Gismondi, A., D'Agostino, A., Ottoni, C., Carra, M., Vukojičić, S., Constantinescu, M., Antonović, D., Price, T.D., Borić, D., 2021. Wild cereal grain consumption among Early Holocene foragers of the Balkans predates the arrival of agriculture. Elife 10, 2021.10.14.464411.
d'Errico, F., Henshilwood, C., Lawson, G., Vanhaeren, M., Tillier, A.-M., Soressi, M., Bresson, F., Maureille, B., Nowell, A., Lakarra, J., Backwell, L., Julien, M., 2003. Archaeological Evidence for the Emergence of Language, Symbolism, and Music–An Alternative Multidisciplinary Perspective. J. World Prehist. 17, 1–70.
de Beaune, S.A., 2004. The Invention of Technology: Prehistory and Cognition. Curr. Anthropol. 45, 139–162.
de Beaune, S.A., 2000. Pour une archéologie du geste (p. 238). CNRS éditions.
de la Torre, I., Benito-Calvo, A., Arroyo, A., Zupancich, A., Proffitt, T., 2013. Experimental protocols for the study of battered stone anvils from Olduvai Gorge (Tanzania). J. Archaeol. Sci. 40, 313–332.
Delgado-Raack, S., Risch, R., 2008. Towards a Systematic Analysis of Grain Processing Technologies. Recent Functional Studies on Non Flint Stones Tools: Methodological

Improvements and Archaeological Inference, in: de Araùjo Ingreja, M., Clemente Conte, I. (Eds.), Recent Functional Studies on Non Flint Stones Tools: Methodological Improvements and Archaeological Inference. pp. 1–20.
Delgado-Raack, S., Menasanch de Tobaruela, J., Bettinardi, I., Soldevilla, J.A., Risch, R., 2022. Surface roughness as a quantitative approach to use-wear on macrolithic tools: A comparative analysis. J. Archaeol. Sci. Rep. 46, 103645.
Dietrich, L., 2021. Plant Food Processing Tools at Early Neolithic Göbekli Tepe. Archaeopress Archaeology, Oxford, England.
Dietrich, L., Götting-Martin, E., Hertzog, J., Schmitt-Kopplin, P., McGovern, P.E., Hall, G. R., Petersen, W.C., Zarnkow, M., Hutzler, M., Jacob, F., Ullman, C., Notroff, J., Ulbrich, M., Flöter, E., Heeb, J., Meister, J., Dietrich, O., 2020. Investigating the function of Pre-Pottery Neolithic stone troughs from Göbekli Tepe – An integrated approach. J. Archaeol. Sci. Rep. 34, 102618.
Dietrich, L., Haibt, M., 2020. Bread and porridge at Early Neolithic Göbekli Tepe: A new method to recognize products of cereal processing using quantitative functional analyses on grinding stones. J. Archaeol. Sci. Rep. 33, 102525.
Dietrich, L., Meister, J., Dietrich, O., Notroff, J., Kiep, J., Heeb, J., Beuger, A., Schütt, B., 2019. Cereal processing at Early Neolithic Göbekli Tepe, southeastern Turkey. PLoS One 14, e0215214.
Dubreuil, L., Savage, D., 2014. Ground stones: a synthesis of the use-wear approach. J. Archaeol. Sci. 48, 139–153.
Dubreuil, L., Hayden, B., Bofill, M., Robitaille, J., 2023. Pounding, grinding, transitioning. A use-wear perspective. J. Archaeol. Sci. Rep. 47, 103743.
Eitam, D., Kislev, M., Karty, A., Bar-Yosef, O., 2015. Experimental barley flour production in 12,500-year-old Rock-Cut mortars in southwestern Asia. PLoS One 10, e0133306.
Filipović, D., Allué, E.A., Boric, D., 2010. Integrated carpological and antracological analysis of plant record from the Mesolithic site of Vlasac, Serbia. Glasnik Srpskog Arheološkog Društva - Journal of the Serbian Archaeological Society 26, 145–161.
Filipović, D., Akšić, M.F., Zagorac, D.D., Natić, M., 2020. Gathered fruits as grave goods? Cornelian cherry remains from a Mesolithic grave at the site of Vlasac, Danube Gorges, south-east Europe. Quat. Int. 541, 130–140.
Filipović, D., Jovanović, J., Rančić, D., 2017. In search of plants in the diet of Mesolithic-Neolithic communities in the Iron Gates. From hunter-gatherers to farmers: human adaptations at the end of the Pleistocene and the first part of the Holocene: papers in honour of Clive Bonsall. Editura Cetatea de Scaun, Targoviște 93–11.
González Carretero, L., Wollstonecroft, M., Fuller, D.Q., 2017. A methodological approach to the study of archaeological cereal meals: a case study at Çatalhöyük East (Turkey). Veg. Hist. Archaeobot. 26, 415–432.
Goren-Inbar, N., Sharon, G., Melamed, Y., Kislev, M., 2002. Nuts, nut cracking, and pitted stones at Gesher Benot Ya'aqov, Israel. Proc. Natl. Acad. Sci. 99, 2455–2460.
Haaland, R., 2007. Porridge and Pot, Bread and Oven: Food Ways and Symbolism in Africa and the Near East from the Neolithic to the Present. Camb. Archaeol. J. 17, 165–182.
Hamon, C., 2022. Use-wear analysis of grinding tools and the exploration of plant processing in the Neolithic of Europe: State of the art and perspectives. J. Archaeol. Sci. Rep. 43, 103471.
Hamon, C., Plisson, H., 2009. Functional analysis of grinding stones: the blind-test contribution, in: Skakun N., L.L. (Ed.), Prehistoric Technology 40 Years Later: Functional Studies and the Russian Legacy. BAR International Series, pp. 29–38.
Hardy, K., Martens, L.K. (Eds.), 2016. Wild harvest: Plants in the hominin and pre-agrarian human worlds, Studying Scientific Archaeology. Oxbow Books, Oxford, England.
Hayes, E., Pardoe, C., Fullagar, R., 2018. Sandstone grinding/pounding tools: Use-trace reference libraries and Australian archaeological applications. J. Archaeol. Sci. Rep. 20, 97–114.
Holst, D., Cristiani, E., Zupancich, A., Calandra, I., 2024. Functional analyses on sandstone slabs from the submerged Mesolithic/Neolithic site of Neustadt LA 156 (Northern Germany). J. Archaeol. Sci. Rep. 56, 104572.
Holst, D., 2021. Equipping the landscape: The use of stationary stones in the early Mesolithic, in: Gaudzinski-Windheuser, S., Jöris., O. (Eds.), The Beef behind All Possible Pasts: The Tandem Festschrift in Honour of Elaine Turner and Martin Street. Propylaeum, pp. 705–723.
Ibáñez, J.J., Mazzucco, N., 2021. Quantitative use-wear analysis of stone tools: Measuring how the intensity of use affects the identification of the worked material. PLoS One 16, e0257266.
Ibáñez-Estévez, J.J., Anderson, P.C., Arranz-Otaegui, A., González-Urquijo, J.E., Jörgensen-Lindahl, A., Mazzucco, N., Pichon, F., Richter, T., 2021. Sickle gloss texture analysis elucidates long-term change in plant harvesting during the transition to agriculture. J. Archaeol. Sci. 136, 105502.
Kabukcu, C., Hunt, C., Hill, E., Pomeroy, E., Reynolds, T., Barker, G., Asouti, E., 2022. Cooking in caves: Palaeolithic carbonised plant food remains from Franchthi and Shanidar. Antiquity 1–17.
Keeley, L.H., Toth, N., 1981. Microwear polishes on early stone tools from Koobi Fora, Kenya. Nature 293, 464–465.
Kozłowski, J.K., Kozłowski, S.K., 1982. Lithic industries from the multi-layer Mesolithic site Vlasac in Yugoslavia. Origin of the chipped stone industries of the early farming cultures in the Balkans. Zeszyty Naukowe Uniwersytetu Jagiellońskiego DCLVIII, Prace Archeologiczne 33, 11–109.
Lippi, M.M., Foggi, B., Aranguren, B., Ronchitelli, A., Revedin, A., 2015. Multistep food plant processing at Grotta Paglicci (Southern Italy) around 32,600 cal BP. Proc. Natl. Acad. Sci. 112, 12075–12080.
Longo, L., Altieri, S., Birarda, G., Cagnato, C., Graziani, V., Obada, T., Pantyukhina, I., Ricci, P., Skakun, N., Sorrentino, G., Terekhina, V., Tortora, L., Vaccari, L., Lubritto, C., 2021. A Multi-Dimensional Approach to Investigate Use-Related Biogenic Residues on Palaeolithic Ground Stone Tools. Environ. Archaeol. 1–29.
Longo, L., Birarda, G., Cagnato, C., Badetti, E., Covalenco, S., Pantyukhina, I., Skakun, N., Vaccari, L., Terekhina, V., Sorrentino, G., 2022. Coupling the beams: How controlled extraction methods and FTIR-spectroscopy, OM and SEM reveal the grinding of starchy plants in the Pontic steppe 36,000 years ago. J. Archaeol. Sci. Rep. 41, 103333.
Macdonald, D.A., Xie, L., Gallo, T., 2019. Here's the dirt: First applications of confocal microscopy for quantifying microwear on experimental ground stone earth working tools. J. Archaeol. Sci. Rep. 26, 101861.
Marinova, E., Filipovic, D., Obradović, D., Allué, E., 2013. Wild plant resources and land use in the Mesolithic and early Neolithic south-east Europe: Archaeobotanical evidence from the Danube catchment of Bulgaria and Serbia. Offa 69, 467–478.
Mariotti Lippi, M., Aranguren, B., Arrighi, S., Attolini, D., Benazzi, S., Boschin, F., Florindi, S., Moroni, A., Negrino, F., Pallecchi, P., Pisaneschi, L., Riel-Salvatore, J., Ronchitelli, A., Revedin, A., 2023. New evidence of plant food processing in Italy before 40ka. Quat. Sci. Rev. 312, 108161.
Marreiros, J., Calandra, I., Gneisinger, W., PaixÃ£o, E., Pedergnana, A., Schunk, L., 2020. Rethinking Use-Wear Analysis and Experimentation as Applied to the Study of Past Hominin Tool Use. J. Paleolithic Archaeol. https://doi.org/10.1007/s41982-020-00058-1.
Marulli, M.R., Sorrentino, G., Menna, F., Paggi, M., 2023. Digital twin models of replicative ground stones: insight into simulating usage of Upper Paleolithic tools. Sci. Rep. 13, 1–10.
Ottoni, C., Borić, D., Cheronet, O., Sparacello, V., Dori, I., Coppa, A., Antonović, D., Vujević, D., Price, T.D., Pinhasi, R., Cristiani, E., 2021. Tracking the transition to agriculture in Southern Europe through ancient DNA analysis of dental calculus. Proc. Natl. Acad. Sci. U.S.A. 118. https://doi.org/10.1073/pnas.2102116118.
Paixão, E., Marreiros, J., Dubreuil, L., Gneisinger, W., Carver, G., Prévost, M., Zaidner, Y., 2021a. The Middle Paleolithic ground stones tools of Nesher Ramla unit V (Southern Levant): A multi-scale use-wear approach for assessing the assemblage functional variability. Quat. Int. https://doi.org/10.1016/j.quaint.2021.06.009.
Paixão, E., Pedergnana, A., Marreiros, J., Dubreuil, L., Prévost, M., Zaidner, Y., Carver, G., Gneisinger, W., 2021b. Using mechanical experiments to study ground stone tool use: Exploring the formation of percussive and grinding wear traces on limestone tools. J. Archaeol. Sci. Rep. 37, 102971.
Pardoe, C., Fullagar, R., Hayes, E., 2019. Quandong stones: A specialised Australian nut-cracking tool. PLoS One 14, e0222680.
Pedergnana, A., Calandra, I., Evans, A.A., Bob, K., Hildebrandt, A., Ollé, A., 2020. Polish is quantitatively different on quartzite flakes used on different worked materials. PLoS One 15, e0243295.
Peña-Chocarro, L., Zapata, L., González Urquijo, J.E., Ibáñez-Estévez, J.J., Moreno García, M., 2005. An ethnoarchaeological project in the western RIF (northern Morocco): First results project in the western RIF (northern Morocco), in: Laboratorio Di Archeobiologia Como. Laboratorio di Archeobiologia Como, p. 2000.
Pichon, F., Ibáñez-Estevez, J.J., Anderson, P.C., Douché, C., Coqueugniot, É., 2021. Harvesting cereals at Dja'de el-Mughara in the northern Levant: New results through microtexture analysis of Early PPNB sickle gloss (11th millennium cal BP). J. Archaeol. Sci. Rep. 36, 102807.
Pichon, F., Ibáñez Estevez, J.J., Anderson, P.C., Tsuneki, A., 2023. Harvesting cereals at Tappeh Sang-e Chakhmaq and the introduction of farming in Northeastern Iran during the Neolithic. PLoS One 18, e0290537.
Proffitt, T., Reeves, J.S., Benito-Calvo, A., Sánchez-Romero, L., Arroyo, A., Malaijivitnond, S., Luncz, L.V., 2021. Three-dimensional surface morphometry differentiates behaviour on primate percussive stone tools. J. r. Soc. Interface 18. https://doi.org/10.1098/rsif.2021.0576.
Radovanović, I., 1996. The Iron Gates Mesolithic. International Monographs in Prehistory Ann Arbor (Michigan).
Revedin, A., Aranguren, B., Becattini, R., Longo, L., Marconi, E., Lippi, M.M., Skakun, N., Sinitsyn, A., Spiridonova, E., Svoboda, J., 2010. Thirty thousand-year-old evidence of plant food processing. Proc Natl Acad Sci U S A 107, 18815–18819.
Revedin, A., Longo, L., Mariotti Lippi, M., Marconi, E., Ronchitelli, A., Svoboda, J., Anichini, E., Gennai, M., Aranguren, B., 2015. New technologies for plant food processing in the Gravettian. Quat. Int. 359–360, 77–88.
Roda Gilabert, X., Martínez-Moreno, J., Mora Torcal, R., 2012. Pitted stone cobbles in the Mesolithic site of Font del Ros (Southeastern Pre-Pyrenees, Spain): some experimental remarks around a controversial tool type. J. Archaeol. Sci. 39, 1587–1598.
Roda Gilabert, X., Mora, R., Martínez-Moreno, J., 2015. Identifying bipolar knapping in the Mesolithic site of Font del Ros (northeast Iberia). Philos. Trans. r. Soc. Lond. B Biol. Sci. 370. https://doi.org/10.1098/rstb.2014.0354.
Roda Gilabert, X., Martínez-Moreno, J., Torcal, R.M., 2016. Ground stone tools and spatial organization at the Mesolithic site of font del Ros (southeastern Pre-Pyrenees, Spain). J. Archaeol. Sci. Rep. 5, 209–224.
Rots, V., 2010. Prehension and Hafting Traces on Flint Tools: A Methodology. Leuven University Press, Leuven.
Sorrentino, G., Menna, F., Remondino, F., Paggi, M., Longo, L., Borghi, A., Re, A., Lo Giudice, A., 2023. Close-range photogrammetry reveals morphometric changes on replicative ground stones. PLoS One 18, e0289807.
Srejović, D., 1969. The roots of the Lepenski Vir culture. Archaeologia Iugoslavica 10, 13–21.
Srejović, D., Letica, Z., 1978. Vlasac: A mesolithic settlement in the iron gates. Serbian Akademie.
Stahl, A., 2014. Plant-food processing and dietary quality, in: Harris, D.R., Hillman, G.C. (Eds.), Foraging and Farming: The Evolution of Plant Exploitation. Routledge, pp. 171–194.
Titton, S., Barsky, D., Bargallo, A., Vergès, J.M., Guardiola, M., Solano, J.G., Jimenez Arenas, J.M., Toro-Moyano, I., Sala-Ramos, R., 2018. Active percussion tools from

the Oldowan site of Barranco León (Orce, Andalusia, Spain): The fundamental role of pounding activities in hominin lifeways. J. Archaeol. Sci. 96, 131–147.

Titton, S., Barsky, D., Bargalló, A., Serrano-Ramos, A., Vergès, J.M., Toro-Moyano, I., Sala-Ramos, R., Solano, J.G., Arenas, J.M.J., 2020. Subspheroids in the lithic assemblage of Barranco León (Spain): Recognizing the late Oldowan in Europe. PLoS One 15, e0228290.

Tringham, R., Cooper, G., Odell, G.H., Voytek, B., Whitman, A., 1974. Experimentation in the Formation of Edge Damage: A New Approach to Lithic Analysis. J. Field Archaeol. 171–196.

van Gijn, A., 2010. Flint in Focus; Lithic Biographies in the Neolithic and Bronze Age. Sidestone Press, Leiden.

Vaughan, P.C., 1985. Use-Wear Analysis on Flaked Stone Tools. University of Arizona Press.

Vitezović, S., 2013. The prehistoric bone tool assemblage from Grivac (central Serbia). Glasnik Srpskog Arheološkog Društva 29, 209–232.

Wright, K., 1991. The Origins and development of ground stone assemblages in Late Pleistocene Southwest Asia. Paléorient 17, 19–45.

Živaljević, I., Dimitrijević, V., Jovanović, J., Blagojević, T., Pendić, J., Putica, A., Uzelac, V., Bulatović, J., Spasić, M., Jončić, N., Penezić, K., Anđelić, D., Bajčeta, M., Stefanović, S., 2021. Revealing the "hidden" Pannonian and Central Balkan Mesolithic: new radiocarbon evidence from Serbia. Quat. Int. 574, 52–67.

Zupancich, A., Cristiani, E., 2020. Functional analysis of sandstone ground stone tools: Arguments for a qualitative and quantitative synergetic approach. Sci. Rep. 10, 15740.

Zupancich, A., Mutri, G., Caricola, I., Carra, M.L., Radini, A., Cristiani, E., 2019. The application of 3D modeling and spatial analysis in the study of groundstones used in wild plants processing. Archaeol. Anthropol. Sci. 11, 4801–4827.

Zvelebil, M., 1994. Plant Use in the Mesolithic and its Role in the Transition to Farming. Proc. Prehist. Soc 60, 35–74.