Eur. Phys. J. Plus (2024) 139:474
https://doi.org/10.1140/epjp/s13360-024-05198-9

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

3D imaging application to the study of the early Neolithic ceramic complex: the decorated pottery of Rio Tana (Abruzzi, Italy)

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Received: 20 December 2023 / Accepted: 20 April 2024

Abstract This study aims to demonstrate the potential of 3D analysis in the study of prehistoric ceramic complexes. Due to the production systems used, prehistoric pottery decorations can vary significantly. Examining the frequency of various decorative methods used at different sites may help identify areas potentially connected to specific traditional elements. However, this is usually a cumbersome and time-consuming task. 3D digital methodologies can bring several advantages in the interpretation of ceramic decoration, providing new tools that can improve analytical skills, speed up the decision process, and support the researcher's conclusions. This work focuses on the application of these methodologies to the study of decorated ceramics from the Neolithic site of Rio Tana (Abruzzo, central Italy): firstly, a pottery complex from this site has been 3D digitised; then, an interactive and web-based 3D visualisation system has been developed to enable access and study of these digital data. By comparing archaeological data with experimental data, in parallel with the analysis of 3D models' surfaces, it has been possible to better define the technique employed and quickly identify the type of tool used to create the ceramic decorations. Furthermore, the web-based system made it possible to share and disseminate the digital dataset with the community, creating the conditions to make it easier to compare the frequency of different decoration methods and tools used at Rio Tana with other sites.

1 Introduction

At the end of the seventh millennium BC, the first groups of farmers arrived at the Apulian coast, bringing with them innovative knowledge and production techniques [1–3]. These communities gradually spread along the two coasts of the peninsula before reaching the Western Mediterranean region [4–7]. Pottery is a significant production of this group and is often used by scholars to understand the cultural context of ancient human groups. Initially, studies primarily focused only on chrono-typological classification [8–11]. Gradually, attention shifted towards technological, productive, and functional aspects [12–19]. In the Western Mediterranean region, the decoration type of pottery served as the foundation for the initial spatial and temporal frameworks related to the extensive "cultural complex of Impressed Wares". Complex divided into various regional synchronic and diachronic facies [20–22].

In the south-central area of the Italian peninsula, the earliest Neolithic sites reveal pottery production with striking similarities, suggesting a common origin [23, 24]. However, the lack of standardisation and homogeneity in the decorative layout, due to varying syntax organisations and the presence or absence of specific motifs, suggests that these human groups probably originated from different geographical areas and traditions, despite belonging to the same Impressed Ware Complex [7, 21, 25].

The decorations on prehistoric pottery exhibit considerable variability because they belong to domestic production systems. Stylistic analysis alone is inadequate to establish accurate affinities or phylogenetic relationships, especially in the early periods. Identifying the possible macro- or micro-areas related to the dissemination and sharing of traditional elements could be facilitated by analysing the frequency of different decorative methods (considering a method composed of multiple attributes such as the decorative forms, tools used, and gestures performed) used at different sites.

Our current research involves developing a holistic method that combines chaîne opératoire analyses, experimental data, traceological analyses, and 3D surface imaging to conduct a more detailed investigation of the pottery decorations and define the process used to create them. Over the past two decades, advancements in 3D digitisation technology have offered a novel approach to capturing and conserving numerical representations of objects in digital format; yet, their use in archaeology is often partial and uneven. In ceramic material research, in the early stages, 3D scanning was mostly employed to produce images of a wide selection of pottery fragments in far less time than traditional manual sketching [26]. Several studies have attempted to utilise its capabilities for identifying uniformity and differences in ceramic production, leading to the creation of a classification system [27, 28], for

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examining the stage of craft development [29, 30], and also to propose a virtual restoration system [31]). A first attempt at a 3D analysis of ceramic decoration, focusing solely on impressed decoration, was recently proposed by Cassard [32].

This article aims to demonstrate the potential of 3D analysis in studying prehistoric ceramic complexes. The study focuses on decorated ceramics from the Neolithic site of Rio Tana in central Italy. The article begins with a brief introduction of the discovery context. It then discusses the results obtained from comparing the 3D data of the archaeological decorations with those obtained from experimental decorations using different techniques and tools. The comparison enabled differentiation between impressed, dragged-impressed, incised, and "graffita" decorations. Additionally, in certain instances, it was possible to accurately identify the morphology and type of instrument used.

2 Corpus studied and archaeological context

We focused our analysis on the pottery complex from sector A (level 1) of the settlement of Rio Tana (Abruzzi region, Italy). The site is located on the south-east terrace of the Fucino basin, in a strategic position, on a narrow plateau in the Vallone Santa Lucia, at an altitude of about 705 m a.s.l. The investigation of the archaeological area [33] allowed us to identify a stratigraphic sequence composed of two main layers (Layers I and II) with a sterile layer of 80 cm between them. The archaeological evidence let us assume the existence of a covered structure dedicated to multiple activities: among these, the treatment of vegetables had to play an important role. Faunal and botanical remains indicate a village with a fully productive economy. Its inhabitants probably had good knowledge of the surrounding area, where they collected different raw materials suitable for lithic and pottery productions. They were likely to be part of an exchange network that favoured the arrival of exotic raw materials such as obsidian from Palmarola and Lipari, volcanic stones from the Southern Apennines, and sea shells. Radiocarbon dating (US3: 6790 ± 70 BP, AECV-211C; US5: 6860 ± 60 BP, AECV-2012C) indicates that the site can be attributed to the early Neolithic period.

The pottery assemblage [34], collected during the archaeological campaigns conducted in 1993 and 2021, shows an abundance of coarse pottery vases with simple shapes, among which the open types prevail. Archaeometric analysis (XRF, SEM–EDS, G. Russo, ongoing analysis) has permitted the recognition of three different fabrics: fine, semi-fine, and coarse. The appearance of the ceramic fragments' sections and surfaces has allowed some insights into the site's firing techniques. The colour of the dough is frequently not uniform and sometimes displays a "sandwich" texture indicative of being fired open hearth (bonfire), with a succession of oxidising and reducing phases. A Zeiss D-7082 Oberkochen microscope equipped with plane cross-polarised light (XPL) has also allowed the observation of the optical activity of the clay matrix and the presence of plant residues. This confirmed that temperatures did not exceed 650 °C. The incidence of decoration is very low: only 75 decorated sherds have been found on a total of 4767 pottery sherds.

3 Methodology

As previously mentioned, the pottery sherds analysis was performed by combining data from different approaches.

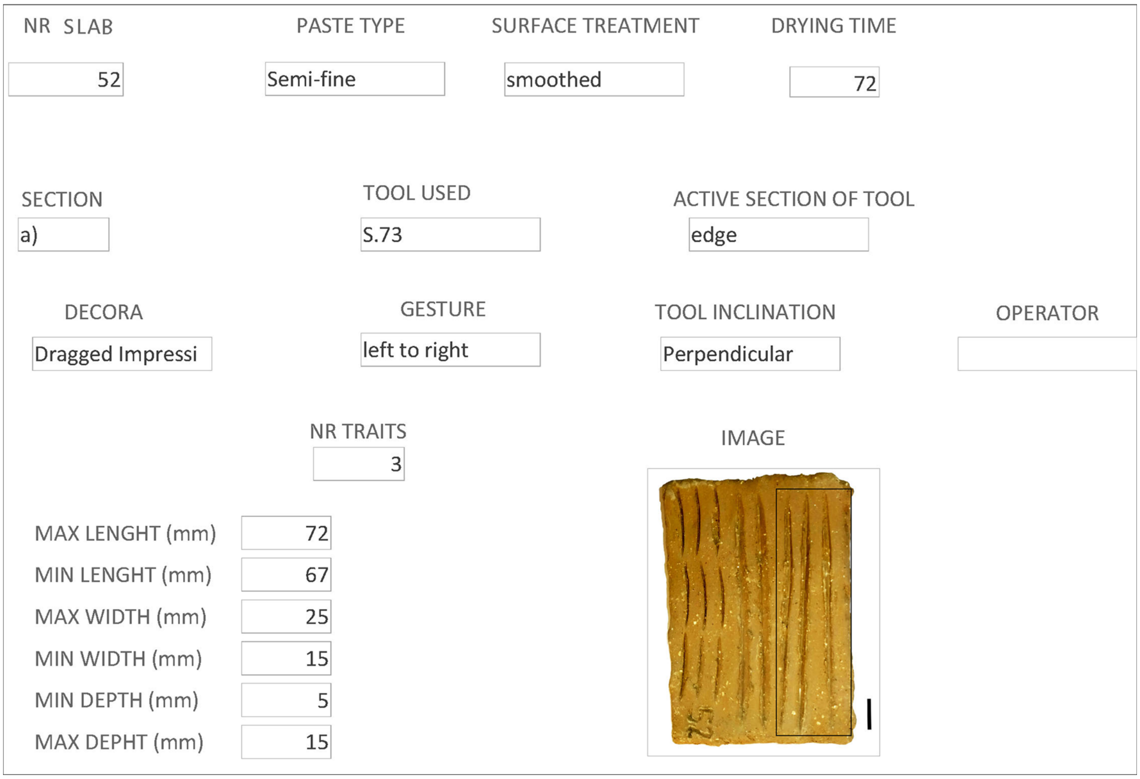
3.1 Experimental data

To gain expertise in the chaîne opératoire of pottery decoration and generate a benchmark collection, an experimental protocol was developed. The raw clay material surrounding the excavation site was selected and processed using information acquired from the archaeometric analyses of the artefacts. Two distinct clay mixtures were prepared: one with a coarse texture and the other with a semi-fine texture, subsequently shaped into rectangular slabs. Different decorations were then made on the slabs and subjected to three different drying periods (24, 48, and 72 h). In line with our observations and recommendations from the literature [35, 36], digital and instrumental techniques were employed to create decorative patterns. We took special care to consider the raw materials and morphology of the tools used and the gestures made, with varying inclinations, in relation to the pottery surfaces. A total of 76 slabs were produced (Fig. 1).

3.2 3D data

Digital copies of the pottery sherds were created to study the decorations analytically. Systems for 3D digitisation are numerous and have been used for more than 20 years to support documentation, study, conservation, and restoration of cultural heritage [37, 38]. Among the various techniques, the most used in the archaeological field are those that use optical sensors, which are preferable because they are typically non-invasive (since they do not require direct contact with the finding). Therefore, for the sherd acquisition, a very high-precision structured light scanner (GOM ATOS) was used (Fig. 2).

This 3D acquisition system is composed of a projector (which projects vertical light patterns on the object to acquire) and two cameras (which capture the coded sequences of stripes after they have been deformed by the object's surface). The scanner reconstructs the 3D shape of the surface portion of the objects that are within the field of view of the cameras (range map) through the principle of triangulation between points in space, using the acquired data and the calibration parameters.



NR SLAB: 52
PASTE TYPE: Semi-fine
SURFACE TREATMENT: smoothed
DRYING TIME: 72

SECTION: a)
TOOL USED: S.73
ACTIVE SECTION OF TOOL: edge

DECORA: Dragged Impressi
GESTURE: left to right
TOOL INCLINATION: Perpendicular
OPERATOR:

NR TRAITS: 3

IMAGE

MAX LENGHT (mm)	72
MIN LENGHT (mm)	67
MAX WIDTH (mm)	25
MIN WIDTH (mm)	15
MIN DEPTH (mm)	5
MAX DEPHT (mm)	15

Fig. 1 Example of a form filled out for experimental slab 52

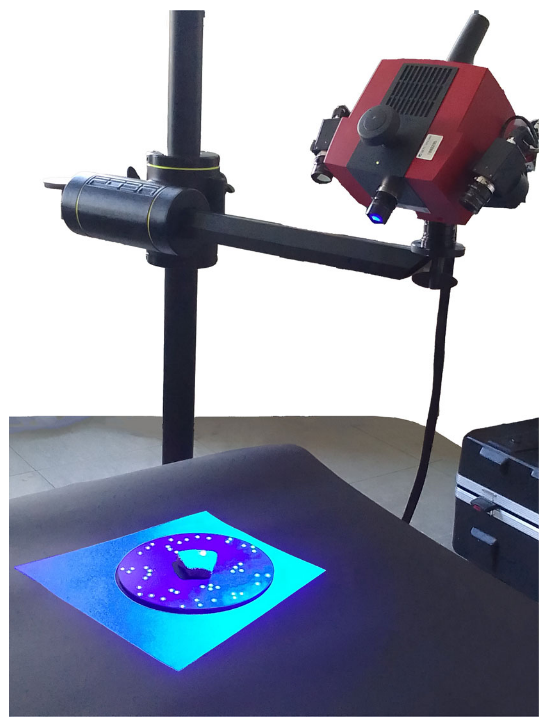


Fig. 2 The GOM ATOS structured light scanner during the digitisation of one of the pottery sherds, placed at the centre of a rotating plate on which various markers have been applied

The complete 3D model is the result of a processing process (registration) that combines multiple range maps, each measuring the surface's geometry from different angles. In the case of the acquisition setup used to digitise the pottery sherds under study, the operating window of each range map covered an area of approximately 40×30 cm (therefore capable of entirely enclosing each sherd), with a resolution of approximately 0.1 mm and 1:1 scale (since each of the points sampled on the object surface corresponds to a point of the digital model with the same spatial coordinates).

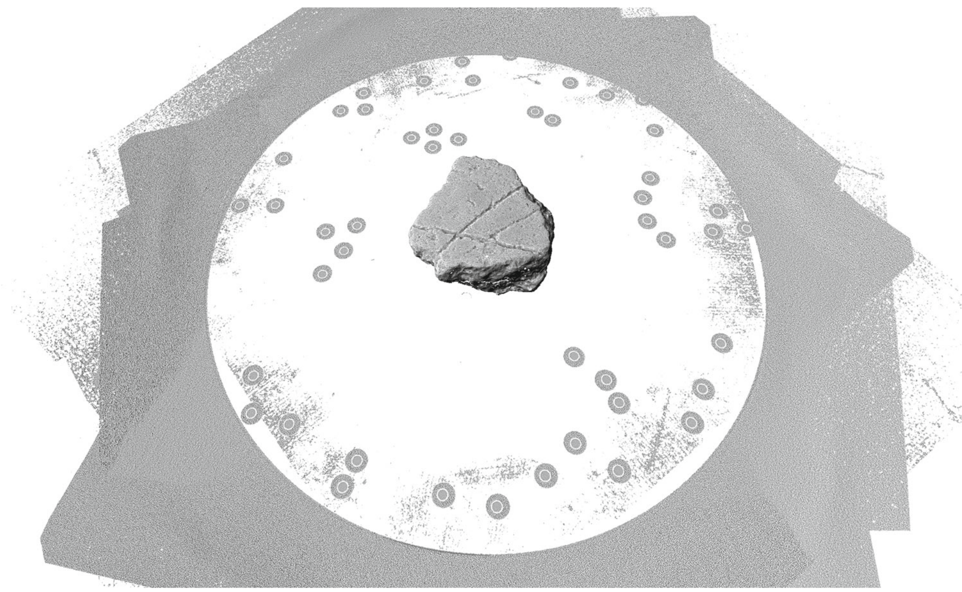


Fig. 3 Example of markers distribution around the sherd to digitise. Markers (the circular elements composed of a point enclosed in a circle) are usually used to improve the registration of the different range maps obtained during the 3D acquisition process

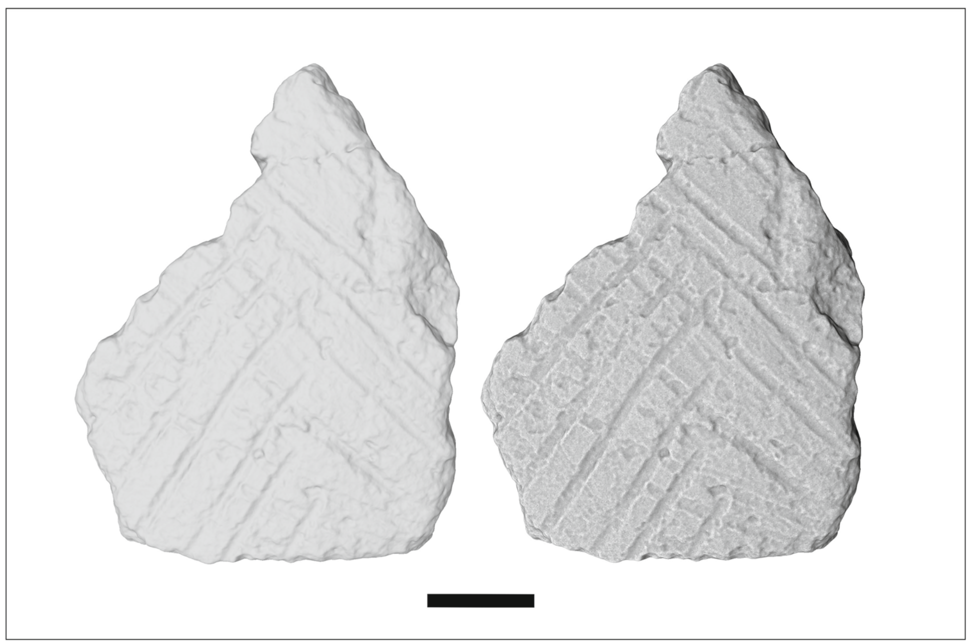


Fig. 4 Example of the radiance scaling rendering technique applied on the 3D model of one of the digitised sherds (scale bar 1 cm). The result (on the right) clearly enhances the depiction of the surface details

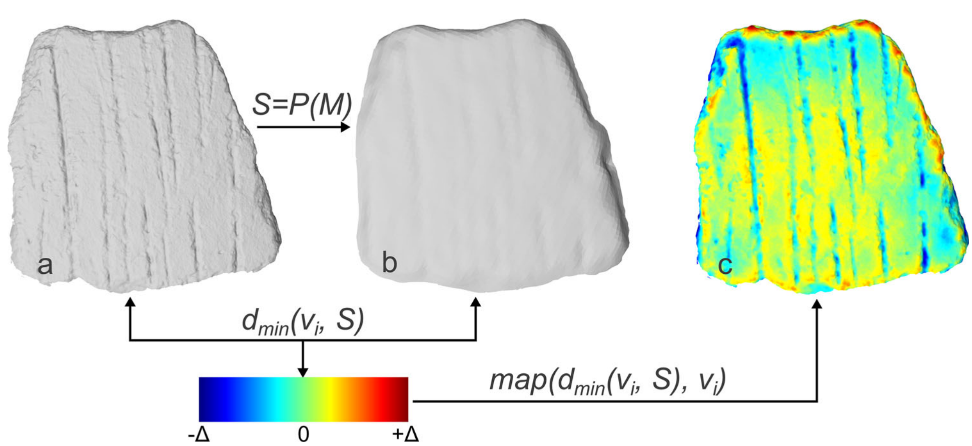


Fig. 5 **a** High-resolution 3D model M. **b** The low-resolution model S is obtained by using the Poisson algorithm on M in order to generate a reference surface. **c** For each vertex v_i of M, the minimum distance from the surface S is calculated and then mapped as colour information onto the corresponding vertex v_i of the mesh M

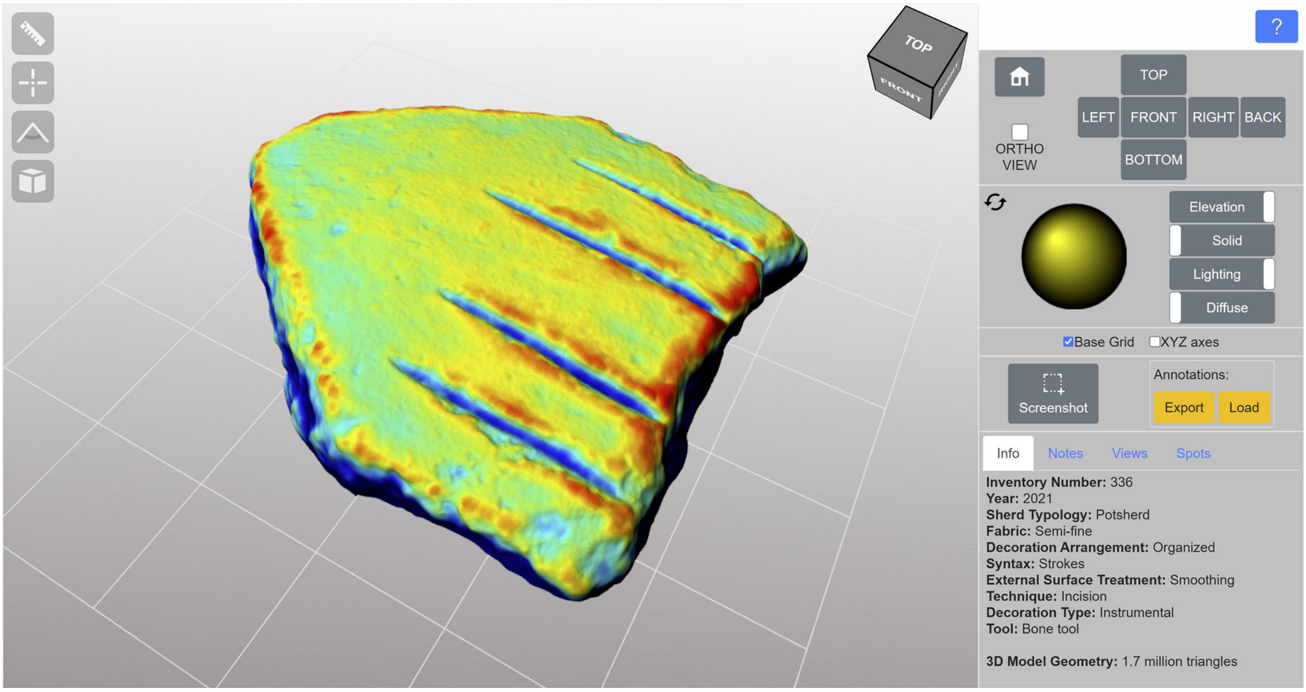


Fig. 6 Screenshot of the online system for sherds' 3D model visualisation. The toolbar with the measurement and section tools is visible on the top-left of the 3D scene, while on the right, there is the panel to access all the other options (rendering, lighting, annotations, etc.)

The different range maps were aligned with each other by exploiting the parts of the geometry in common and the markers present in the scene. Using markers (Fig. 3) during the acquisition of range maps is a common technique to facilitate the registration phase and enhance accuracy since it helps to calculate the roto-translation that aligns each new range map with those previously acquired, thus making it easier to place them in the correct position.

The digitisation, the data control, an initial cleaning, and a first alignment of the range maps were performed in semi-automatic mode by the ATOS Professional software (version 8, build 2015.04.22), which controls the 3D scanner. All the data collected were then exported and processed using MeshLab[1] (software version 2022.02), a 3D model processing and visualisation software developed by ISTI-CNR [39]. The data processing in MeshLab consisted of cleaning and filtering of the range maps, fine alignment of the scans, generation of the triangulated surface, cleaning of the 3D model, orientation, and positioning of the model. The resulting 3D models have a level of geometric detail of approximately a 0.1 mm. With this geometric sampling step, the digital models can be considered metric copies of the original pottery sherds and can be used to document their state of conservation at the time of digitisation, but also to perform in-depth study and analysis activities that exploit the digital format. In fact, the 3D models' surface can be mapped data and information derived from specific scientific analyses and imaging techniques. Ambient occlusion and radiance scaling [40] are examples of two well-known shading and rendering techniques that can significantly enhance the details of a 3D surface (Fig. 4).

Moreover, other solutions can be developed ad hoc, tailored to the specific case study. For the pottery sherds of Rio Tana, a new method has been implemented to automatically make the engravings present in the findings easier to read (Fig. 5). The method consists in comparing the high-resolution 3D model of each sherd (Fig. 5a) with a hypothetical reference surface obtained from the same data, on which there are no details. The comparison surface can be obtained by applying the low-resolution Poisson reconstruction algorithm [41] to the 3D data, which allows the elimination of high-frequency details while maintaining the overall shape of the object (Fig. 5b).

A colour that encodes the distance between the two surfaces (deviation map) is mapped at each point of the high-resolution model (Fig. 5c). This measure highlights the engravings on the pottery sherds making them easier to identify, and at the same time, it provides an instant map useful for estimating their depth.

Based on open-source software components, this method is rapid to implement, accessible, and replicable (it does not rely on complex computational infrastructures, nor does it require reimplementing ad hoc code), and therefore easy to use in a standard pipeline.

Through software specialised in 3D visualisation/editing (such as MeshLab), it is possible for experts to interact with the 3D models created, performing measurements, evaluations, and analysis using their own PC. However, the use of these tools, highly

[1] https://www.meshlab.net.

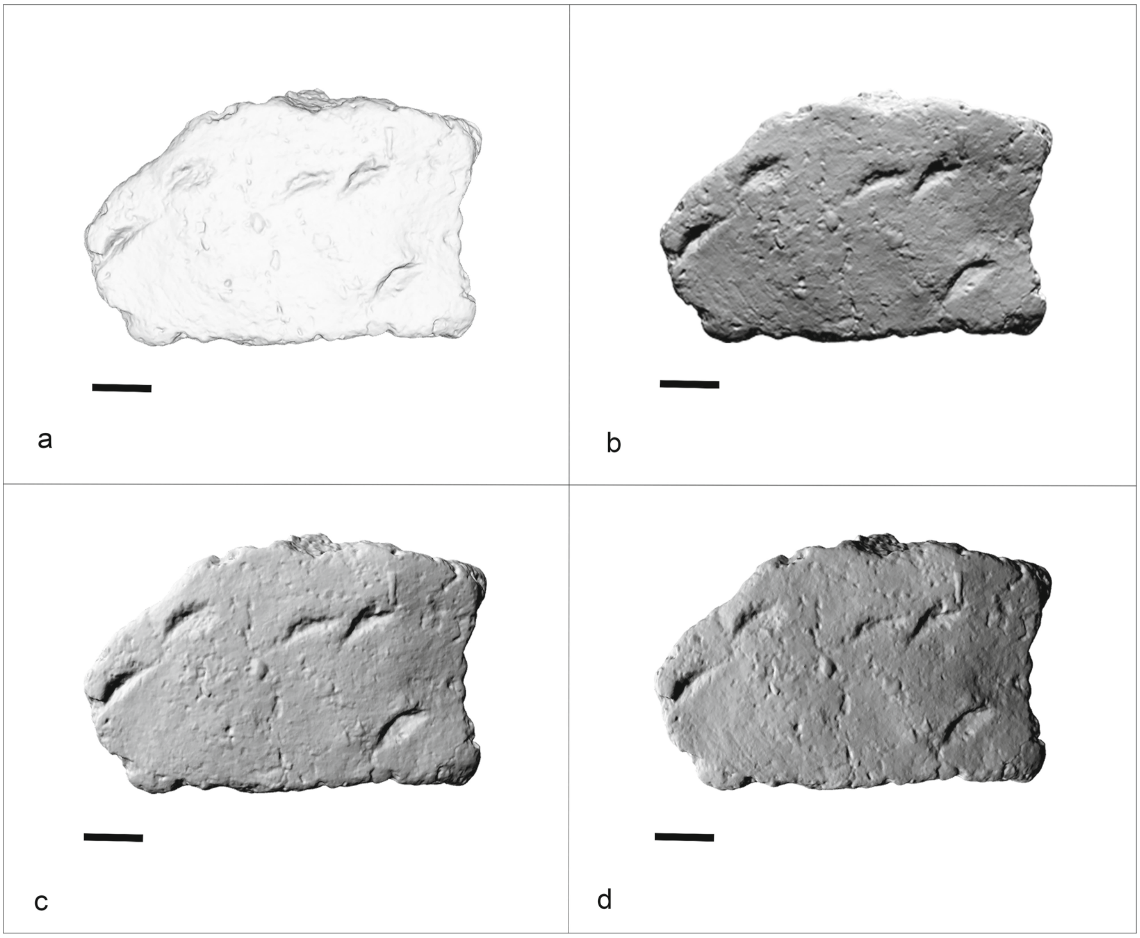


Fig. 7 Multiple views of fragment 1 with variations in the lighting conditions (scale bar 1 cm). **a** Default light; **b** Top light; **c** Top-left light; **d** Bottom-left light

specialised and aimed at 3D experts, is sometimes not immediate for non-experts, narrowing the field of analysis possibilities for scholars with different backgrounds.

For this reason, a 3D visualisation system[2] has been developed specifically to assist non-3D experts in the study of engravings (Fig. 6). Based on 3DHOP—3D Heritage Online Presenter[3] (software version 4.3.4), a framework developed by ISTI-CNR that allows the management of complex 3D data online [42], the system enables the interactive visualisation of the sherds' digital models directly in the web browser, without the need to install any specific software. Exploiting the multi-resolution streaming and rendering engine provided by 3DHOP, it is possible to explore not only the high-resolution 3D models of the pottery sherds but also all the calculated analytical data mapped on their surface.

By default, the developed system enables the visualisation of the sherds' 3D geometries, represented in a solid grey colour. This allows users to focus on the morphologic structure of the digitised findings, which can be explored from different perspectives and at various zoom levels.

A simple toolbar provides several measurement tools, enabling accurate analysis of the engravings' features and dimensions (width, length, depth, and angle) directly on the 3D model. Furthermore, the same toolbar provides users with a tool able to generate 3D sections, allowing a detailed view of the profiles of the incisions.

Through a specific panel, it is possible to access several rendering options (solid, transparent, specular, and diffuse) and the different types of information that can be mapped onto each 3D model, including the aforementioned deviation map, which provides an immediate and interactive 3D view of the depth variations of the examined grooves.

From the same panel, it is possible to control the 3D scene lighting, by varying the angle of incidence of an artificial point light source in real-time to highlight the characteristics of the surface engravings.

2 https://vcg.isti.cnr.it/EPJPlus/index.html.

3 https://3dhop.net.

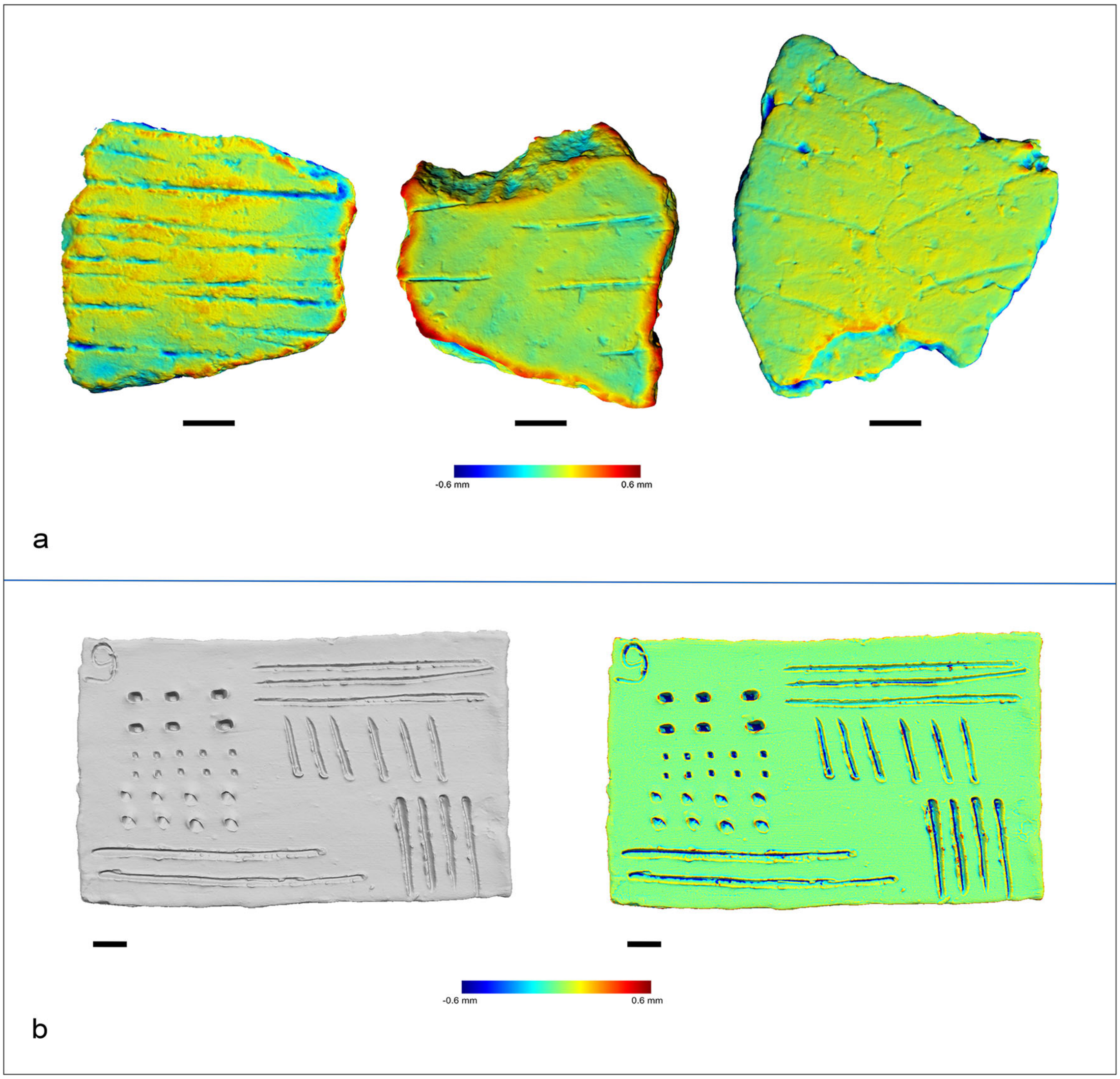


Fig. 8 Colour deviation maps. Through colour changes, differences in depth are highlighted on the surface of the fragments (scale bar 1 cm). **a** Colour deviation maps of sherds 210, 292 and 2; **b** Colour deviation maps of experimental slab 9

The system also provides the possibility to switch between orthographic and perspective projection, to recall different visual bookmarks that automatically align the digital model to the canonical views (front, back, left, right, top, and bottom), and to visualise together with the 3D model a reference grid for correctly sizing it.

Through the system's user interface, it is also possible to add textual notes and comments, associating them with specific points of view, or to specific points on the 3D model. Finally, the system allows the online sharing of data, analyses, and annotations, enabling collaboration and establishing a distributed work environment.

4 Discussion

The use of 3D scanning and visualisation tools has allowed a more detailed analysis of the decorative traces considered for the study. Using the 3DHOP-based system, it was possible not only to perform macro-like zooms of the surface details, but also to arbitrarily orient the light source of the model (Fig. 7) to obtain better visibility of the decorative traces and thus identify their topography, as well as quantitative data. Accurate measurements of length, width, and depth, together with the possibility to access different types of informative visualisation modes (like for instance cross-sections and deviation maps), have been essential to define the individual parts of the decorative pattern (Fig. 8). The web system has enabled fast and ubiquitous data access, making it possible to perform all the aforementioned visual analyses in a much more immediate and focused way. Moreover, the support for collaborative

Table 1 List of decorated fragments

NR	NR. invent	Year	Sherd typology	Fabric	Decoration arrangement	Syntax	External surface treatment	Technique	Decoration type	Tool
1	3	2021	Potsherd	Coarse	Organised	Lines	Smoothing	Incision	Instrumental	Animal organic matter tool
2	63		Rim	Coarse	Horizontal	Lines	Smoothing	Incision	Instrumental	n.d
3	64	2021	Potsherd	Semi-fine	Organised complex	Grid	Smoothing	Incision	Instrumental	Smoothed edge shell
4	106	2021	Potsherd	Semi-fine	Covering	Lines	Smoothing	Incision	Instrumental	n.d
5	172	2021	Potsherd	Semi-fine	Covering	Lines	Smoothing	Incision	Instrumental	n.d
6	292	2019	Potsherd	Semi-fine	Organised	Strokes	Smoothing	Incision	Instrumental	Soft needle-like tool (quill/feather)
7	302	2019	Potsherd	Semi-fine	Covering	Pinched marks	Smoothing	Impression	Digital	Finger
8	311	2021	Potsherd	Semi-fine	Covering	Pinched marks	Smoothing	Impression	Digital	Finger
9	316	2019	Potsherd	Semi-fine	Organised	Segments	Smoothing	Impression	Instrumental	n.d
10	336	2021	Potsherd	Semi-fine	Organised	Strokes	Smoothing	Incision	Instrumental	Bone tool
11	348	2021	Potsherd	Coarse	Covering	Notches	Smoothing	Impression	Instrumental	n.d
12	363	2019	Potsherd	Coarse	Organised	Filled band	Smoothing	Mixed technique	Instrumental	Notched edge shell + n.d. tools
13	365	2021	Potsherd	Fine	n.d	Pinched mark	Smoothing	Impression	Digital	Finger
14	379	2019	Potsherd	Semi-fine	Organised	Strokes	Smoothing	Incision	Instrumental	Animal organic matter tool
15	381	2019	Potsherd	Semi-fine	Covering	Nail marks	Smoothing	Impression	Digital	Nail
16	409	2019	Potsherd	Semi-fine	Organised	Segments	Smoothing	Impression	Instrumental	Notched edge shell
17	434		Potsherd	Semi-fine	Organised	Lines	Smoothing	Incision	Instrumental	n.d
18	435	2021	Inflessione	Coarse	Organised	Chevron	Smoothing	Incision	Instrumental	Lithic tool
19	437	2021	Potsherd	Fine	n.d	Line	Smoothing	Incision	Instrumental	n.d
20	440	2021	Potsherd	Coarse	Organised	Lines	Smoothing	Incision	Instrumental	n.d
21	441	2021	Potsherd	Coarse	Organised	Segment	Smoothing	Impression	Instrumental	Notched edge shell
22	1	1993	Rim	Semi-fine	Organised	Filled band	Hard smoothing	Mixed technique	Instrumental	Notched edge shell + n.d
23	2	1993	Potsherd	Coarse	Organised	Chevron	Smoothing	Incision	Instrumental	Animal organic matter tool
24	3	1993	Potsherd	Coarse	Organised	Nail marks	Smoothing	Impression	Digital	Nail
25	4	1993	Base	Semi-fine	n.d	Lines	Smoothing	Impression	Instrumental	Notched edge shell
26	5	1993	Potsherd	Coarse	Organised	Strokes	Hard smoothing	Incision	Instrumental	Lithic tool
27	6	1993	Rim	Semi-fine	Covering	Pinched marks	Smoothing	Impression	Digital	Nail
28	7	1993	Potsherd	Coarse	Covering	Lines	Smoothing	Incision	Instrumental	n.d
29	8	1993	Potsherd	Coarse	n.d	Pinched marks + segments	Smoothing	Impression	Mixed technique	Nail + Notched edge shell
30	9	1993	Potsherd	Semi-fine	Covering	Lines	Smoothing	Incision	Instrumental	n.d

Table 1 continued

NR	NR. invent	Year	Sherd typology	Fabric	Decoration arrangement	Syntax	External surface treatment	Technique	Decoration type	Tool
31	10	1993	Potsherd	Coarse	n.d	Line	Smoothing	Incision	Instrumental	n.d
32	11	1993	Potsherd	Coarse	n.d	Marks	Smoothing	Impression	Instrumental	Notched edge shell
33	12	1993	Potsherd	Coarse	Organised	Strokes	Smoothing	Incision	Instrumental	Smoothed edge shell
34	13	1993	Potsherd	Semi-fine	Organised	Strokes	Smoothing	Incision	Instrumental	Bone tool
35	14	1993	Potsherd	Semi-fine	Covering	Chevron	Smoothing	Incision	Instrumental	n.d
36	15	1993	Potsherd	Coarse	Covering	Nail marks	Smoothing	Impression	Digital	Nail
37	16	1993	Potsherd	Coarse	Covering	Segments	Smoothing	Incision	Instrumental	Notched edge shell
38	17	1993	Potsherd	Coarse	Organised	Segments	Smoothing	Incision	Instrumental	Vegetal matter tool
39	18	1993	Potsherd	Coarse	n.d	Segment	Smoothing	Incision	Instrumental	n.d
40	19	1993	Rim	Semi-fine	n.d	Line	Smoothing	Incision	Instrumental	Bone tool
41	20	1993	Inflessione	Coarse	n.d	Lines	Smoothing	Incision	Instrumental	n.d
42	21	1993	Potsherd	Coarse	n.d	Marks	Smoothing	Impression	Instrumental	Notched edge shell
43	22	1993	Potsherd	Coarse	n.d	Lines	Smoothing	Impression	Instrumental	n.d
44	23	1993	Base	Semi-fine	Organised	Strokes	Smoothing	Incision	Instrumental	Smoothed edge shell
45	24	1993	Potsherd	Coarse	Covering	Marks	Smoothing	Impression	Instrumental	n.d
46	25	1993	Potsherd	Coarse	Covering	Segments	Smoothing	Incision	Instrumental	n.d
47	26	1993	Potsherd	Coarse	Covering	Segments	Smoothing	Incision	Instrumental	n.d
48	27	1993	Potsherd	Fine	n.d	Marks	Hard smoothing	Impression	Instrumental	n.d
49	29	1993	Potsherd	Coarse	Organised	Lines	Smoothing	Impression	Instrumental	Notched edge shell
50	30	1993	Potsherd	Coarse	Covering	Nail marks	Smoothing	Impression	Digital	Nail
51	173	1993	Rim	Semi-fine	Covering	Wolf tooth	Smoothing	Incision	Instrumental	n.d
52	196	1993	Potsherd	Coarse	Organised	Strokes	Smoothing	Incision	Instrumental	Vegetal matter tool
53	197	1993	Potsherd	Coarse	n.d	Lines	Smoothing	Incision	Instrumental	n.d
54	198	1993	Potsherd	Coarse	n.d	Lines	Smoothing	Incision	Instrumental	Smoothed edge shell
55	199	1993	Potsherd	Coarse	n.d	Lines	Smoothing	Incision	Instrumental	n.d
56	200	1993	Potsherd	Coarse	n.d	Lines	Hard smoothing	Incision	Instrumental	n.d
57	201	1993	Potsherd	Coarse	n.d	Lines	Smoothing	Incision	Instrumental	n.d
58	202	1993	Potsherd	Coarse	Organised	Strokes	Smoothing	Incision	Instrumental	Bone tool
59	203	1993	Potsherd	Semi-fine	n.d	Strokes	Smoothing	Incision	Instrumental	n.d
60	204	1993	Potsherd	Coarse	n.d	Strokes	Smoothing	Incision	Instrumental	n.d
61	205	1993	Potsherd	Coarse	Organised	Segments	Smoothing	Incision	Instrumental	Smoothed edge shell (?)
62	206	1993	Rim	Semi-fine	Organised	Strokes	Smoothing	Incision	Instrumental	Bone tool
63	207	1993	Rim	Coarse	Organised	Segments	Smoothing	Incision/Impression?	Instrumental	Lithic tool/Smoothed edge shell?
64	208	1993	Rim	Semi-fine	Organised complex	Chevron + strokes	Hard smoothing	Incision	Instrumental	Bone tool
65	209	1993	Potsherd	Coarse	Organised	Lines	Smoothing	Impression?	Instrumental	Notched edge shell?

Table 1 continued

NR	NR. invent	Year	Sherd typology	Fabric	Decoration arrangement	Syntax	External surface treatment	Technique	Decoration type	Tool
66	210	1993	Potsherd	Semi-fine	Organised	Lines + strokes	Hard smoothing	Incision	Instrumental	Lithic tool
67	211	1993	Potsherd	Coarse	Organised	Lines	Smoothing	Impression?	Instrumental	Smooth edge shell?
68	212	1993	Potsherd	Coarse	n.d	Line	Smoothing	Incision	Instrumental	n.d
69	213	1993	Potsherd	Coarse	Organised	Marks	Smoothing	Impression	Instrumental	Notched edge shell?
70	214	1993	Potsherd	Coarse	Organised complex	Lines	Smoothing	Incision	Instrumental	Lithic tool
71	215	1993	Rim	Semi-fine	n.d	Pinched mark	Smoothing	Impression	Digital	Finger
72	216–217	1993	Potsherd	Semi-fine	Organised	Lines + marks	Hard smoothing	Impression	Instrumental	n.d
73	218	1993	Potsherd	Coarse	n.d	Marks	Smoothing	Impression?	Instrumental	n.d
74	219	1993	Potsherd	Semi-fine	Organised	Filled band	Smoothing	Mixed technique	Instrumental	Notched edge shell + n.d.?
75	220	1993	Potsherd	Semi-fine	Organised	Segments	Smoothing	Incision	Instrumental	n.d

data study/annotation provided by the same platform allowed the researchers involved in this project to exchange information and considerations remotely, speeding up the analytical process (a possibility potentially open to the entire community).

The comparison of data obtained from experimental and archaeological artefacts has allowed the determination of the morphology and, in most cases, the type of tool used to form the various decorations (Table 1). In some cases, previous attributions made with the naked eye have been corrected. Close examination of the traces has revealed a lack of uniformity in the depth of the strokes, and the identification of drag marks, which have made it possible to define as incised decorations what at first sight appeared to be impressions.

The most observed decorative technique is incision, featuring either simple motifs such as lines or segments or organised motifs such as parallel lines or grids, covering either the entire surface of the fragment or isolated areas. The depth of the stroke varies from very deep to superficial.

The use of tools of different types was detected, including shells (Fig. 9), lithic blades (Fig. 10), spatulas, and points made from both bone (Fig. 11) and plant material (Fig. 12).

At Rio Tana, the occurrence of this incision technique reaches over 70%. These results are partially in line with information from other Central Adriatic sites from the same chronological period. Incised ornamentation constitutes 60% of the decorative technique at nearby ancient Neolithic sites, located in the Fucino area including Colle Santo Stefano [43, 44], Paterno [45], Ortucchio-laghetto [46, 47], Ortucchio Sant'Orante [48], and Grotta Continenza [49, 50]. The data from the remainder of the Abruzzo-Marche region (Maddalena di Muccia [51–53], Piani di Calisti di Esanatoglia [54], and Portonovo di Ancona [55] are more divergent, as the number of incisions is considerably lower than that of the impressions.

There is a lack of precise information in the literature regarding the tools employed to produce the decorations on the aforementioned sites. The available general descriptions merely offer a possible list through assessments of visible marks made with the naked eye.

Although only a small number of impressed specimens are present (<30% of decoration), the prevalence of digital pinched decoration (Fig. 13b) and instrumental impressions over the use of the shell (Fig. 13a) relates Rio Tana to the sites along the Abruzzo–Marchigiana area (Middle Adriatic facies) [56], rather than the neighbouring Fucino sites. The latter exhibits a good incidence of impressed decoration, with syntaxes such as rocker, microrocker, and sequence patterns, indicating similarities with the south–east areas (facies with southern affinities), whereas at Rio Tana these are few.

As shown in the previous examples, examining 3D data can aid in identifying the decorative pattern and the type of instrument used. This is accomplished by observing the shape, individual features, and surface topography. Furthermore, this digital dataset allows for the reconstruction of gestures and the chronology of actions performed (see Figs. 14b and 15b). Some elements show complex decorative syntaxes that cover the central band of the vase in an organised way (Table 1 n: 12, 22, 74). Occasionally, the decoration is a combination of different motifs and styles (Fig. 14). In fragment 1, the series of parallel shell impressions appears to have been made before the two incised lines that contain them. This element, along with the others decorated with rocker, is one of those suggesting links with the southern sphere.

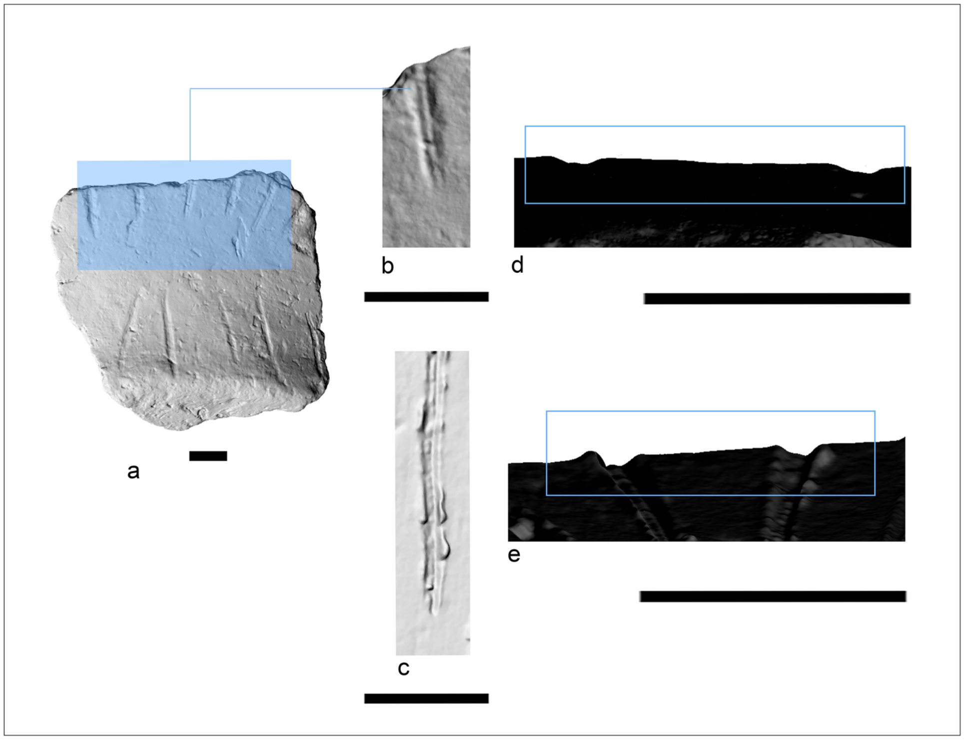


Fig. 9 Comparison of archaeological traces on sherd 23 with experimentally obtained traces (scale bar 1 cm). **a** Sherd 23 with decoration performed with a shell. The incision has smooth walls and a long striation at the base due to the growth lines of the shell; **b** Close-up of the archaeological traces; **c** Close-up of the experimental trace; **d** Cross-section of the archaeological trace; and **e** Cross-section of the experimental trace. The experimental trace (image c) shows a difference in depth and accumulations of clay at the edges, suggesting a shorter drying time compared to fragment 23 and a greater pressure applied with the instrument. In the archaeological fragment, the surfaces appear more regular due to the smoothing action carried out after the decoration

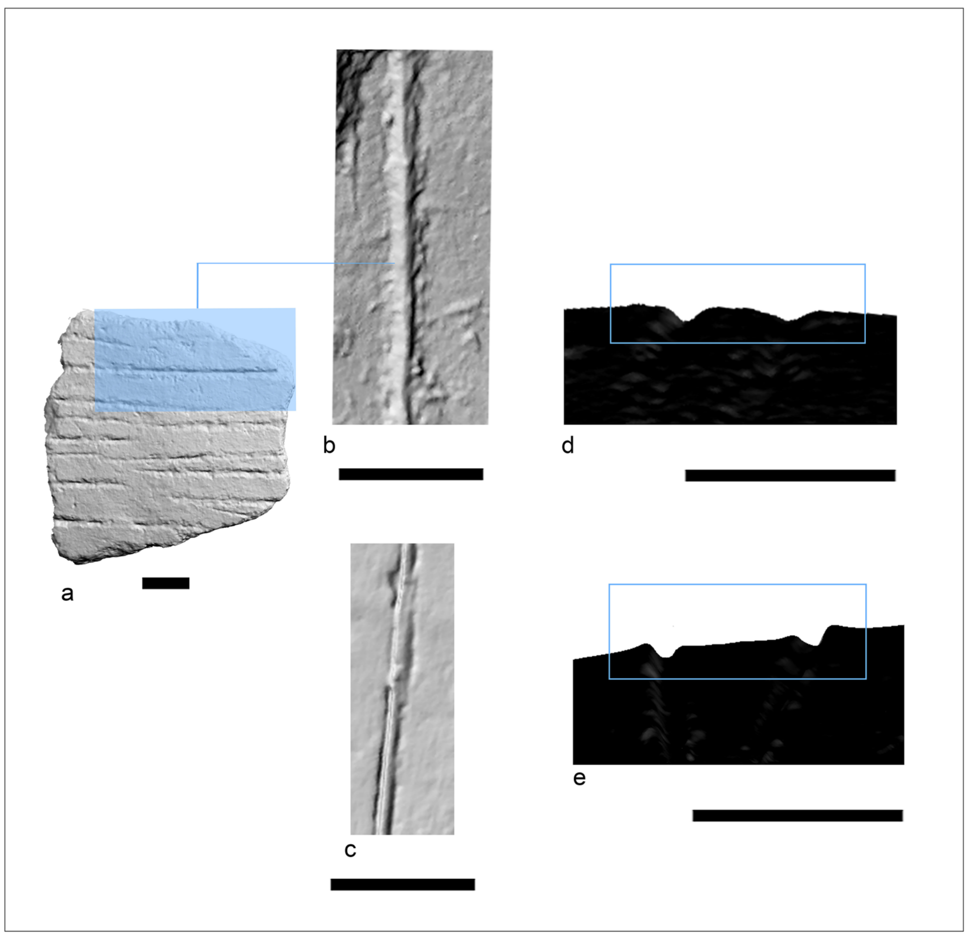


Fig. 10 Comparison of archaeological traces on sherd 210 with experimentally obtained traces (scale bar 1 cm). **a** Sherd 210 decorated with lithic tools. The incisions are linear, with a V-shaped cross-section. The inner walls of the incision are very smooth. **b** Close-up of the archaeological traces; **c** Close-up of the experimental trace; **d** Cross-section of the archaeological trace; and **e** Cross-section of the experimental trace. In the archaeological fragment, the upper part of the edge of the decorative features appears more regular due to the surface's smoothing action carried out after the decoration. Moreover, in the archaeological fragment, the upper portion of the edge of the decorative features appears more regular due to the surface's smoothing action that was carried out after the decoration

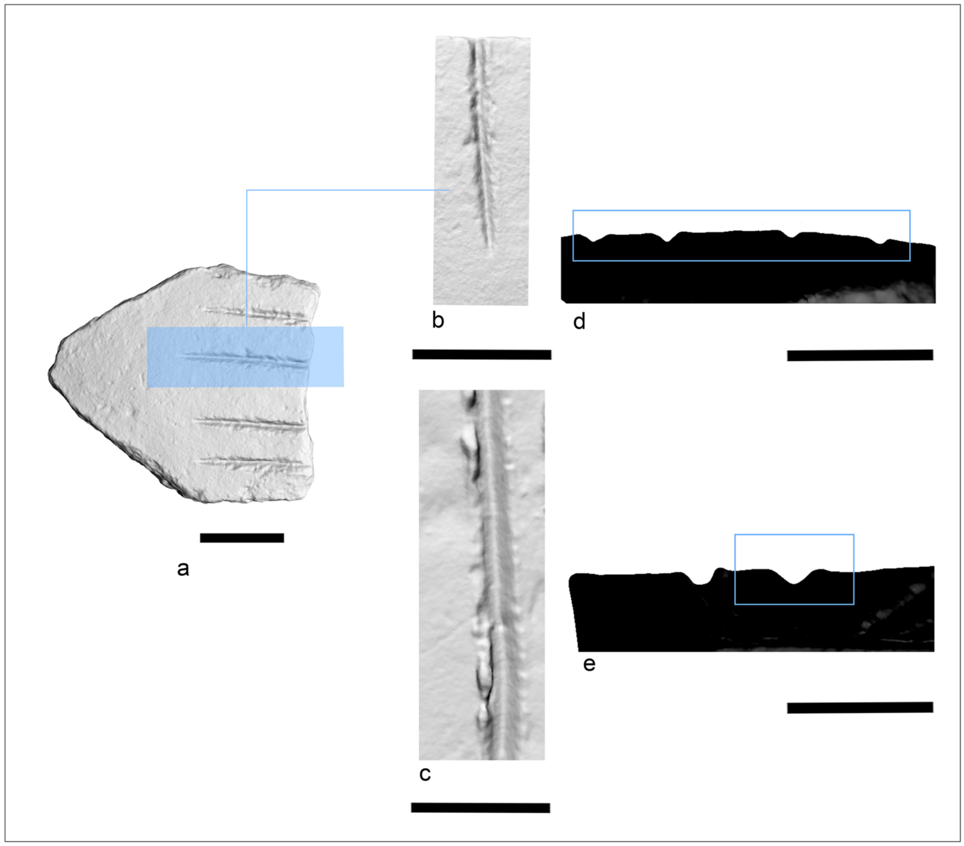


Fig. 11 Comparison of archaeological traces on sherd 336 with experimentally obtained traces (scale bar 1 cm). **a** Sherd 336 decorated with a tool made of hard animal material, probably bone. The surface of the inner walls of the incision is smooth, and the base shows short parallel narrow striations due to the natural structure of the bone; **b** Close-up of the archaeological traces; **c** Close-up of the experimental traces; **d** Cross-section of the archaeological trace; and **e** Cross-section of the experimental trace. The difference in tool dimensions is responsible for the difference in trace dimensions seen in the d and e images. In the archaeological fragment, the surfaces appear more regular due to the smoothing action carried out after the decoration process

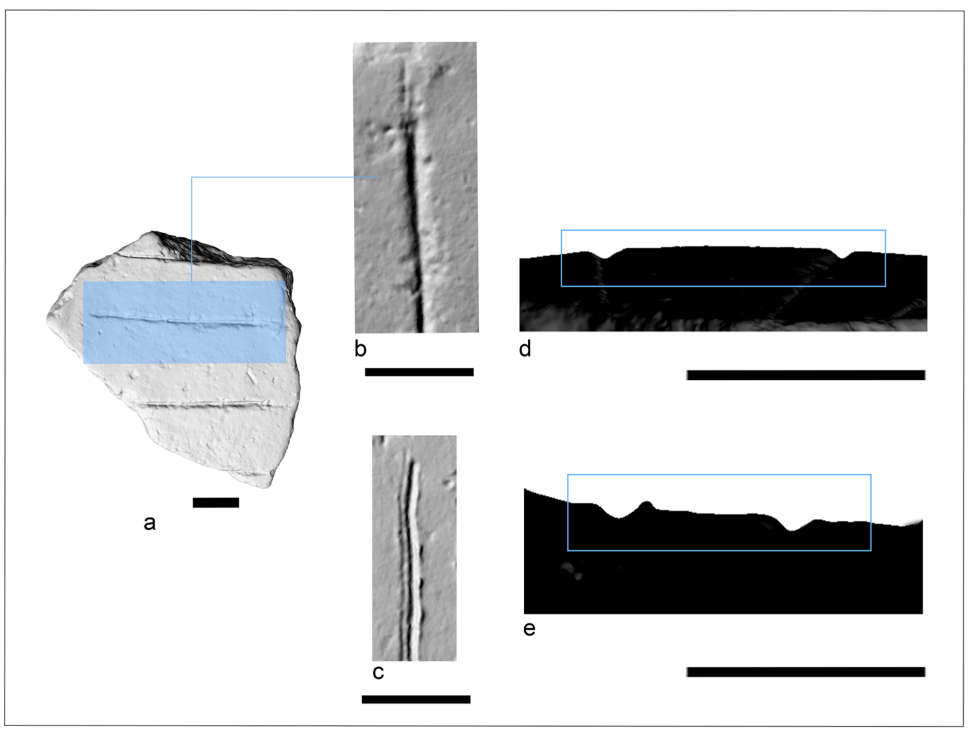


Fig. 12 Comparison of archaeological traces on sherd 196 with experimentally obtained traces (scale bar 1 cm). **a** Sherd 196 with incision characterised by a wavy surface of the base, due to the dragging of a thin and slightly flexible pointed tool, probably made in vegetal matter; **b** Close-up of the archaeological traces; **c** Close-up of the experimental trace; **d** Cross-section of the archaeological trace; and **e** Cross-section of the experimental trace. The difference in the size of the features and the outline of the upper part of the edges is due to the different dimensions of the tools used and to the different stages of drying of the surfaces. In the archaeological fragment, the surface appear more regular due to the smoothing action carried out after the decoration

In pottery sherd 64 (Fig. 15), a grid decoration comprising several overlapping incised lines is observable. A chronological scheme of actions can potentially be proposed for this decoration (Fig. 15b). The vertical lines (in accordance with the orientation presented in Fig. 15) were produced sequentially after the horizontal ones, from top to bottom. Clay material, which has been pulled

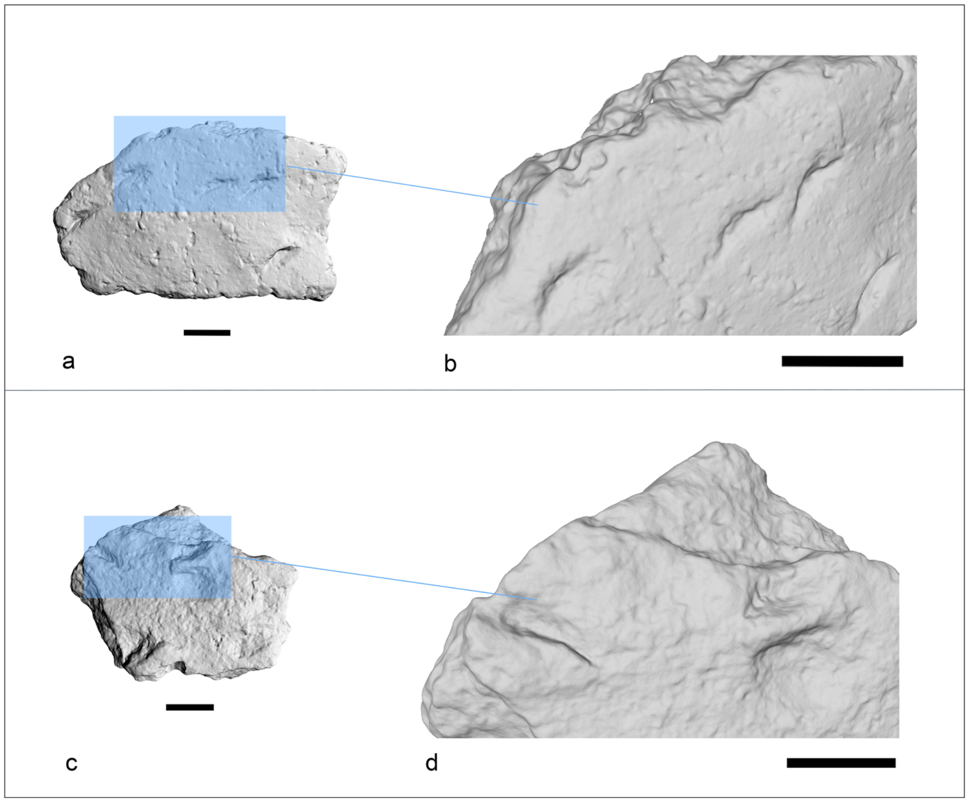


Fig. 13 **a**, **b** Pottery fragment decorated with shell impressions (scale bar 1 cm); **c**, **d** Pottery fragment decorated with opposing nail impressions (scale bar 1 cm)

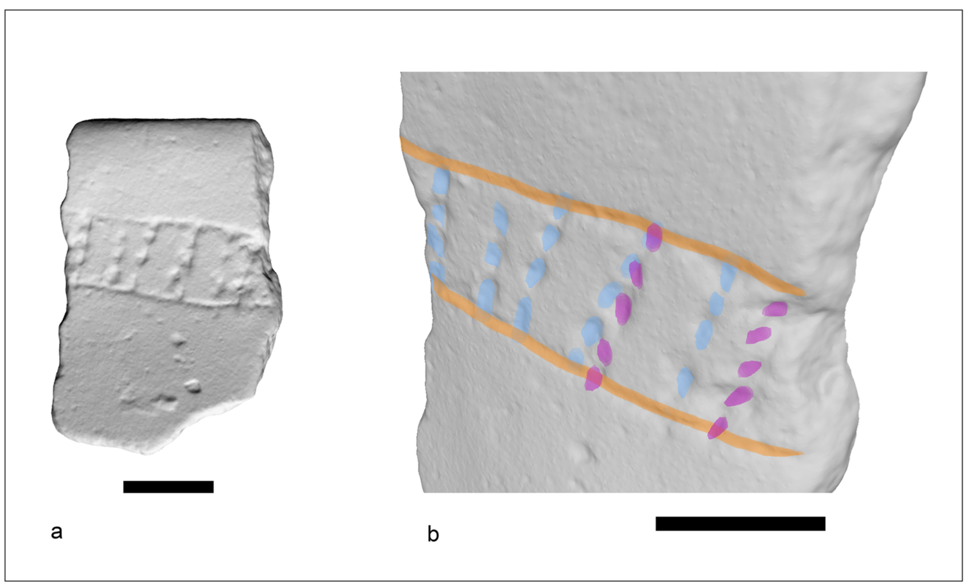


Fig. 14 **a** 3D models of sherd 1 (scale bar 1 cm); **b** Chronology of actions: step 1) impressions probably made with a notched edge shell (blue), step 2) the two parallel incised lines (orange), step 3) other two impressions made with the notched edge shell (violet)

in the direction of the tool's movement, is evidently visible at the points of intersection (Fig. 15c). The superimposed 'V' incised motifs and the grids are related to the Adriatic area (Colle Santo Stefano, Grotta dei Piccioni).

5 Conclusion

This paper proposes an innovative approach to the study of prehistoric pottery by combining 3D imaging with experimental data. The use of 3D digital technologies has demonstrated several advantages in the interpretation of ceramic decoration, providing new tools that can improve analytical skills, speed up the decision process, and support the researcher's conclusions.

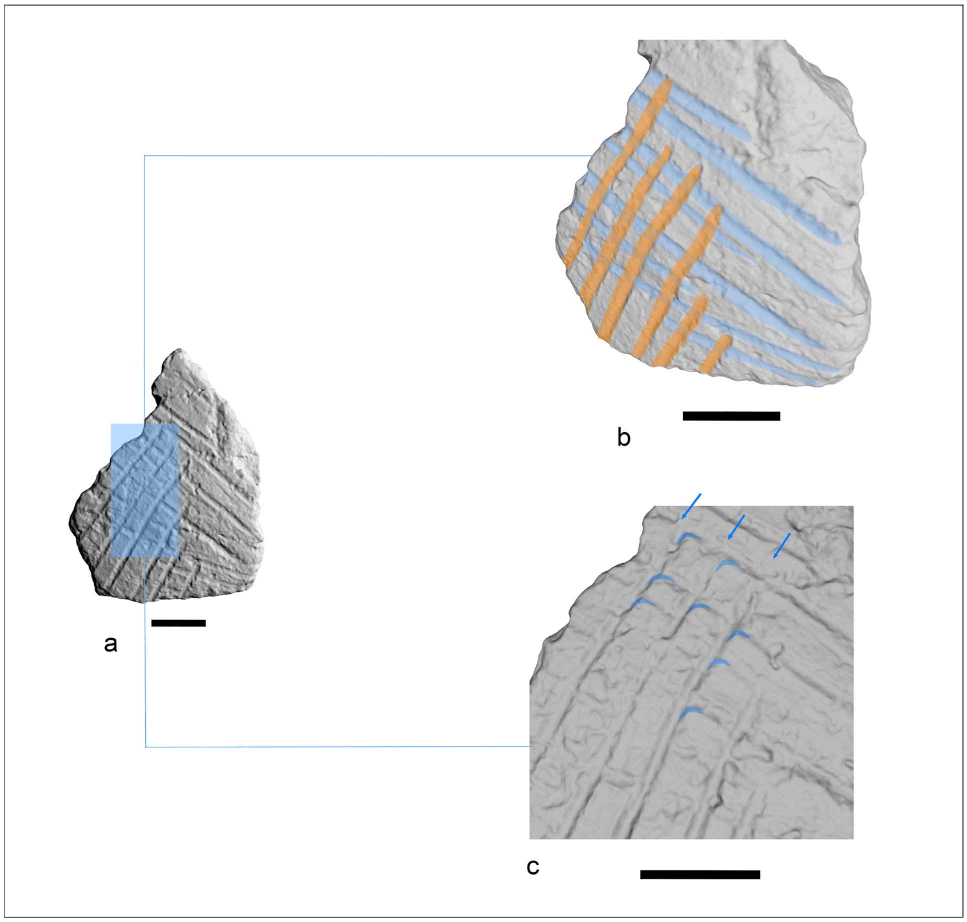


Fig. 15 **a** Fragment 64 showing a complex decoration (scale bar 1 cm); **b**, **c** Chronology of the gestures made to create the decorative scheme

The comparison of archaeological and experimental data by means of the 3D digitised dataset has allowed a meticulous identification of the shape of each mark, and a metric analysis of the stigmata created by the tool used. The tools provided by the interactive visualisation system have enabled new points of view on the studied sherds, allowing for instance to remove the original colour from the digitised sherds to better appreciate their surface geometry, or to examine the sections of the digital models to get insight on the depth of the carvings. These tools have been crucial in determining the technique, the type of tools, and, in some instances, the raw material used. In some cases, the 3D digital models have made it possible to reinterpret some of the interpretations made by the naked eye in the first instance: decorative features that appeared to have been obtained by impression turned out to have been obtained by incision. This confirms that the methodology presented in this work can be a valid complement to classical analysis techniques, that not only helps isolate the features necessary to correctly identify the technique or tool used, but also contributes to fastening the identification/comparison process. In fact, a collection of digital objects, if correctly stored and managed in a proper web-based platform, enables quick and ubiquitous data access, not always possible with the corresponding physical objects.

The data available for the Central Adriatic area present a diverse range of pottery production, but its features have not yet been well defined [21]. While the pottery assemblage analysed in this study only represents a sector of the ancient village of Rio Tana, it provides valuable insight into the production choices made during the early stages of the Neolithic period. The complex was dated between 5600 and 5500 BC using radiometric dating of carbon and seeds. The vessels, technological choices, and decorative techniques used in the village are partly comparable to those found in the Central Adriatic and southern regions, although they differ from both. This suggests that during the Early Neolithic, communities in the Adriatic region were integrated into exchange networks. These networks facilitated the introduction of ideas and models that were received and reinterpreted differently by individual local communities. Currently, the literature lacks sufficient information on the tools used for ceramic decoration at individual sites, which could aid in identifying micro-areas of common use or tradition. Therefore, future studies should aim to comprehensively analyse these aspects. The introduction of a methodology based on 3D digitisation could facilitate the collection and dissemination of this data. The web-based visualisation system introduced in this work enables researchers to share data online, promoting collaboration and creating an open and user-friendly data network. The validity of this approach has already proven to be valid during the preparation of this work, since the remote system has been widely exploited by the two different research groups (archaeologists and computer scientists) that collaborated on this project, to share considerations, analysis, and requests. However, the potential of this system remains largely unexplored. For this reason, future work is specifically aimed at building an expanded and more structured archaeological digital dataset, to be made available to experts and scholars active in this research field.

Acknowledgements This research is a product of the ADMIRE project (investigAte 3D iMaging neolIthic ceRamic dEcoration), research aimed at studying prehistoric ceramic decoration as a proxy to identify the existence of possible phylogenetic links and common traditions between the earliest farming communities. The project is supported by the Department of Civilisation and Forms of Knowledge of the University of Pisa and by the "Alessandro Faedo" Institute of Information Science and Technologies of the CNR of Pisa.

Author contributions Conceptualization was contributed by Alice Vassanelli, Cristiana Petrinelli Pannocchia, and Agnese Terranova; methodology and experimental approach were involved by Alice Vassanelli, Cristiana Petrinelli Pannocchia, and Agnese Terranova; 3D imaging was performed by Marco Potenziani, Paolo Pingi, Marco Callieri, and Paolo Cignoni; formal analysis and investigation were attributed by Alice Vassanelli, Cristiana Petrinelli Pannocchia, and Agnese Terranova]; writing—original draft preparation did by Cristiana Petrinelli Pannocchia; writing—review and editing was done by Cristiana Petrinelli Pannocchia, Alice Vassanelli, Agnese Terranova, Marco Potenziani, Paolo Pingi, tables and images editing were responsible by Agnese Terranova, Marco Potenziani, and Paolo Pingi.

Funding Open access funding provided by Università di Pisa within the CRUI-CARE Agreement. This project was supported by the Department of Civilizations and Forms of Knowledges – University of Pisa (Department of Excellence Program and PRA_2022_17_Pratiche artigiane tra Mediterraneo ed Oriente. Studi interdisciplinari dalla Preistoria al Medioevo, resp. prof. S. Menchelli).

Data Availability Statement Data will be made available on request. The manuscript has associated data in a data repository.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

References

1. J. Guilaine, Zephyrus **53–54**, 267–272 (2001)
2. J. Zilhão, PNAS **98**(24), 14180–14185 (2001). https://doi.org/10.1073/pnas.241522898
3. J. Guilaine, G. Cremonesi, *Torre Sabea: Un Établissement du Néolithique Ancien en Salento (Collection de l'Ecole Française de Rome 315* (Publicationps de l'Ecole Française de Rome, Roma, 2003)
4. D. Binder, J.E. Brochier, H. Duday, D. Helmer, P. Marinval, S. Thiebault, J. Wattez, Gall. Préhist. **35**, 177–251 (1993)
5. D. Binder, R. Maggi, BSPF **98**(3), 411–422 (2001)
6. J. Guilaine, C. Manen, J.D. Vigne, P. Ambert, *Nouveaux Regards sur la néolithisation de la France Méditerranéenne* (Archives d'Ecologie Préhistorique, Toulouse, 2007)
7. G. Radi, C.P. Pannocchia, Quat. Int. **470**, 270–284 (2018). https://doi.org/10.1016/j.quaint.2017.06.063
8. A. Furumark, *The Mycenaean Pottery. Analysis and Classification* (Kungl. Vitterhets Historie och Antikvitets Adademien, Stockholm, 1941)
9. R. Whallon, Am. Antiq. **37**, 13–33 (1972)
10. M.A. Fugazzola Delpino, A. Pessina, V. Tiné, *Le Ceramiche Impresse nel Neolitico Antico: Italia e Mediterraneo* (Istituto poligrafico e Zecca dello Stato, Roma, 2002)
11. P.M.M.G. Akkermans, G.M. Schwartz, *The Archaeology of Syria. From Complex Hunter-Gatherers to Early Urban Societies (ca. 16,000–300 BC)* (Cambridge University Press, Cambridge, 2003)
12. F. Giligny, S. Méry, *Approches de la chaîne opératoire de la céramique. Le façonnage* (Les Nouvelles de l'archéologie 119, Charenton-le-Pont, 2010) https://doi.org/10.4000/nda.950
13. J.M. Skibo, *Understanding Pottery Function* (Springer, 2013)
14. B. Van Doosselaere, L. Burnez-Lanotte, L. Gomart, A. Livingstone Smith, Notae Praehistoricae **33**, 15–26 (2013)
15. L. Gomart, *Traditions Techniques et Production Céramique au Néolithique Ancien. Étude de Huit Sites Rubanés du Nord-Est de la France et de Belgique* (Sidestone Press, Leiden, 2014)
16. J.M Skibo, in *Use-wear and residue analysis in archaeology*, eds. By J.M. Marreiros, J.F.G. Bao, N.F. Bicho (Springer, 2015), pp. 189–198
17. V. Roux, *De Céramiques et des Hommes* (presses universitaires de Paris Nanterre, Paris, 2017)
18. L. Fanti, Riv. Sci. Priest. LXIX, pp. 23–56 (2019)
19. G. Montana, Archaeol. Anthropol. Sci.**12**, 175 (2020). https://doi.org/10.1007/s12520-020-01130-1
20. D. Binder, in *Chronologies néolithiques. De 6000 à 2000 avant notre ère dans le Bassin rhodanien, Ambérieuen-Bugey*, ed. by J.L. Voruz (Société préhistorique rhodanienne, Documents du Département d'Anthropologie et d'Écologie de l'Université de Genève, 1995) pp. 55–65
21. D. Binder, C. Manen, *Céramiques Imprimées de Méditerranée Occidentale (VIe millénaire AEC): Données, Approches et Enjeux Nouveaux / Western Mediterranean Impressed Wares (6th millennium BCE): New Data, Approaches and Challenges, Actes de la Séance de la SPF, 18* (Société Préhistorique française, Paris, 2022)
22. C. Manen, T. Perrin, J. Guilaine, L. Bouby, S. Bréhard, F. Briois, P. Durand, P. Marinval, J.-D. Vigne, Radiocarbon **61**(2), 531–571 (2019)

23. M. Cipolloni Sampò M., C. Tozzi, M.L. Verola, in *Le Néolithique du Nord-Ouest Méditerranéen*, ed. By J. Vaquer, XXIV Congrès Préhistorique de France (Carcassonne, 1999) pp. 39–50
24. V. Tiné, in *Le Ceramiche Impresse nel Neolitico Antico. Italia e Mediterraneo*, eds. by A. Pessina, V. Tiné (Istituto poligrafico e Zecca dello Stato, Roma, 2002) pp. 132–165
25. C. Manen, in *La Transition Néolithique En Méditerranée. Archives d'Ecologie Préhistorique*, eds. by C. Manen, T. Perrin, J. Guilaine (Toulouse, 2014), pp. 405–418
26. R. Sablatnig, C. Menard, in *The Third International Symposium on Computing and Archaeology*, eds. by P. Moscati, S. Mariotti (Rome, 1996), pp. 429–446
27. K. Adler, M. Kampel, R. Kastler, M. Penz, R. Sablatnig, K. Schindler, in *Proc. of 6th Intl. Workshop on Archaeology and Computers*, eds. by W. Börner, L. Dollhofer (Vienna, 2002), pp.3–12
28. M. Kampel, R. Sablatnig, Pattern Recogn. Lett.**28**(6), 740–747 (2007). https://doi.org/10.1016/j.patrec.2006.08.011
29. A. Karasik, U. Smilansky, J. Archaeol. Sci.**35**(5), 1148–1168 (2008). https://doi.org/10.1016/j.jas.2007.08.008
30. L. Di Angelo, P. Di Stefano, A.E. Morabito, C. Pane, Measurements **124**, 138–146 (2018). https://doi.org/10.1016/j.measurement.2018.04.016
31. M. Zhou, G. Geng, Z. Wu, Z., W.A. Shui, in *Proceedings of the CAA Conference 37th Computer applications and quantitative methods in archaeology* (Williamsburg, 2010), pp. 391–396
32. L. Cassard, S. Sorin, G. Durrenmath, D. Binder, in *Céramiques Imprimées de Méditerranée Occidentale (VIe Millénaire AEC): Données, Approches et Enjeux Nouveaux / Western Mediterranean Impressed Wares (6th millennium BCE): New Data, Approaches and Challenges*, eds. by D. Binder, C. Manen, Actes de la séance de la SPF (Société Préhistorique française, Paris, 2022), pp. 349-378
33. C. Petrinelli Pannocchia, A. Vassanelli, Y. Naime, A. Terranova, S. Sani, L. Spadacini, E. Ceccaroni, in *Il Fucino e le aree limitrofe nell'antichità, Atti del IV Convegno di Archeologia* (Avezzano, 2022)
34. C. Petrinelli Pannocchia, A. Vassanelli, A. Terranova, ALD III, 13–25 (2023) https://doi.org/10.13131/unipi/27ez-ah42
35. E. Natali, The Old Potter's Almanack **19**(2), 2–13 (2015). https://doi.org/10.11588/opa.2014.2.18268
36. C. Manen C., L. Salanova, in *Premières sociétés paysannes de Méditerranée occidentale. Structures des productions céramiques*, eds. by C. Manen, F. Convertini, D. Binderand I. Sénépart (Société préhistorique française, Mémoires 51, Paris, 2010) pp.57–64
37. R. Scopigno, M. Callieri, P. Cignoni, M. Corsini, M. Dellepiane, F. Ponchio, G. Ranzuglia, Computer **44**(7), 48–55 (2011). https://doi.org/10.1109/MC.2011.196
38. M. Dellepiane, M. Callieri, M. Corsini, R. Scopigno, in *Digital Imaging for Cultural Heritage Preservation: Analysis, Restoration and Reconstruction of Ancient Artworks*. ed. by F. Stanco, S. Battiato, G. Gallo (CRC Press, Boca Raton, 2011), pp.39–72
39. P. Cignoni, M. Callieri, M. Corsini, M. Dellepiane, F. Ganovelli, G. Ranzuglia, Sixth Eurographics Italian Chapter Conference (2008), pp. 129–136 https://doi.org/10.2312/LocalChapterEvents/ItalChap/ItalianChapConf2008/129-136
40. R. Vergne, R. Pacanowski, P. Barla, X. Granier, C. Schlick. Radiance Scaling for versatile surface enhancement. In Proceedings of the 2010 ACM SIGGRAPH symposium on Interactive 3D Graphics and Games (I3D '10). Association for Computing Machinery, New York, NY, USA, pp. 143–150. https://doi.org/10.1145/1730804.1730827
41. M. Kazhdan, H. Hoppe, ACM Trans. Graph. **32**(3), 1–13 (2013). https://doi.org/10.1145/2487228.2487237
42. M. Potenziani, M. Callieri, M. Dellepiane, M. Corsini, F. Ponchio, R. Scopigno, Comput. Graph.**52**, 129–141 (2015). https://doi.org/10.1016/j.cag.2015.07.001
43. Radi G, in *Le ceramiche impresse nel Neolitico antico. Italia e Mediterraneo*, eds. by M.A. Fugazzola Delpino, A. Pessina, V. Tiné (Istituto Poligrafico e Zecca dello Stato, Rome, 2002) pp. 509–524
44. C. Fabbri, C. Petrinelli Pannocchia, G. Radi, in *Il Fucino e le aree limitrofe nell'antichità, Atti del III Convegno di Archeologia* (Avezzano, 2011), pp. 119–131
45. A. Pessina, *Il Fucino e le aree limitrofe nell'antichità, Atti del Convegno di Archeologia* (Lithoprint De Cristofaro, Rome, 1991), pp.11–133
46. C. Fabbri, L. Angeli, AGOGÈ IV-V, 17–36 (2009)
47. L. Angeli, O. Ventura, in *Il Fucino e le aree limitrofe nell'antichità, Atti del III Convegno di Archeologia* (Avezzano, 2011), pp. 542–545
48. V. D'Ercole, S. Festuccia, E. Remotti, *in Il Fucino e le aree limitrofe nell'Antichità, Atti II Convegno di Archeologia* (Celano 2001), pp. 82–87
49. A. Barra, R. Grifoni Cremonesi, F. Mallegni, M. Piancastelli, A. Vitiello, B. Wilkens, Riv. Sci. Preist. XLII, 31–100 (1989–1990)
50. R. Grifoni Cremonesi, in *Le ceramiche impresse nel Neolitico antico. Italia e Mediterraneo*, ed. by M.A. Fugazzola Delpino, A. Pessina, V. Tiné (Istituto Poligrafico e Zecca dello Stato, Rome, 2002) pp. 525–540
51. D.G. Lollini, *Atti del VI Congresso Internazionale delle Sci. Preist. e Protost*. II (IIPP, Firenze, 1965), pp. 309–315
52. D. Lollini, *Museo archeologico nazionale delle Marche*. Sezione preistorica Paleolitico-Neolitico (Falconara: Errebi, 1991)
53. M. Silvestrini, A. Manfredini, G. Radi, in *Problemi e prospettive di ricerca*, *Atti XXXVIII Riun. Scient*. IIPP (IIPP, Firenze, 2005) pp. 221–230
54. C. Conati Barbaro, C. La Marca, D. Pellegrini, D. D'Errico, S.M. Stellacci, Riv. Sci. Preist. LXXII, 1–27 (2022) https://doi.org/10.32097/1155
55. C. Conati Barbaro, *Il Fuoco e la Memoria. I Forni Neolitici di Portonovo* (Milleni: Studi di Archeol. Preist. 21, 2019)
56. B. Bagolini, P. Von Eles, Preist. Alp. **14**, 33–63 (1978)