A traceological and quantitative assessment of the function of the bone bi-pointed tools from the Late Neolithic of the Cueva del Toro (Antequera, Malaga).

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Abstract

This study presents a traceological analysis of bi-pointed bone tools from the Late Neolithic layers of Cueva del Toro (Málaga, Spain). The tools, previously hypothesized as arrowheads, were re-examined using traceological methods combined with confocal microscopy. The analysis refutes their classification as hunting implements. Polished surfaces on the tools, indicative of interaction with fibrous materials, suggest their use in weaving tasks involving wool or similar materials. This study highlights the early use of sheep wool for textiles at Cueva del Toro, dated between 4250 and 3950 cal BCE. This study also emphasizes the significance of craft activities in the Neolithic, with a diverse toolkit for processing fibers and animal materials. By applying quantitative methods to distinguish use-wear traces, the study contributes to the development of use-wear analysis techniques and opens the way for future research in ancient human-material interactions.

Keywords:

Cueva del Toro, bone tools, traceological analysis, confocal microscopy, Late Neolithic, fibre processing, weaving, plant materials, wool, functional analysis, craft activities.

Introduction

The use of textiles represents an extremely significant chapter in the cultural and technological evolution of human communities from the Paleolithic period onward.

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Direct and indirect evidence suggests the manufacture and weaving of textiles, basketry, and cordage from vegetal raw materials since at least 30,000 years ago (Adovasio et al. 1996; Soffer et al. 2000; Kvavadze et al. 2009; Kilgore & Gonthier 2014). However, it is with the advent of the Holocene that we observe a profound expansion in the use and manipulation of weaving materials. Plant-based fibers were widely utilized during the Mesolithic and Early Neolithic phases. Strings and basketry made from a variety of species, such as rushes (*Phragmites australis*), reeds (*Juncus sp.*), flax (*Linum usitatissimum*), hemp (*Cannabis sativa*), lime (*Tilia sp.*) and oak (*Quercus sp.*) bast, and esparto grass (*Stipa tenacissima*), were likely common, with abundant evidence found across Europe and the Near East (see Mineo et al. 2023 for a recent review). Furthermore, the introduction of agriculture and animal husbandry provided an additional supply of raw materials—wheat, flax, and wool, among others—fueling the innovation and diversification of textile production techniques. An increase in textile production has often been associated with the so-called Secondary Production Revolution (Sherratt 1981, 1983; Greenfield 2010), from the 4th millennium onward, when the use of plant fibers was complemented by the innovation of wool weaving, marking a significant advancement in textile technology. However, our current understanding of the origins of wool production remains limited. Unambiguous genetic and biological markers for the exploitation of animal fibers have yet to be identified (Saña & Tornero 2012). Only through the integration of multiple indicators related to animal slaughtering, management, mobility, and feeding patterns, along with the study of artifacts involved in wool gathering, processing, and finishing, can we gain new insights into the beginnings of wool exploitation. This article aims to provide new data on weaving technology during the Late Neolithic, focusing on one of the most promising contexts for the study of Neolithic crafting practices: Cueva del Toro (Antequera, Spain).

Archaeological context

Cueva del Toro is located in the Torcal Mountains, in the municipality of Antequera. This mountainous range extends over 27 km, with elevations ranging between 800 and 1,400 meters above sea level. The geographical coordinates of Cueva del Toro are: 36º 57’ 23” North latitude and 4º 32’ 10” West longitude, situated at an altitude of 1,190 meters (Fig. 1). Archaeological excavations have revealed a significant stratigraphic sequence, identifying various occupational layers from different periods of Prehistory. This has allowed for the establishment of a chronology spanning from the mid-6th millennium BCE to the first quarter of the 5th millennium BCE, all within the context of Phase IV of the site, corresponding to the Early Neolithic. Furthermore, the subsequent sequence is organized into two subphases. The lower subphase- corresponding to the Late Neolithic (Subphase IIIb) – extends from last quarter of the 5th millennium BCE until the first centuries of the 4th millennium BC, while the upper subphase, Subphase IIIa, associated with the Late Recent Neolithic period, concludes in the last quarter of the 4th millennium BC. Moving on to the upper levels, a new occupational phase (Phase II) is highlighted, with its earliest foundation, related to Subphase Iib, corresponding to the Chalcolithic (Martín Socas et al. 2004; Camalich Massieu and Martín Socas 2013; Égüez et al. 2016) (cf. Fig.1).

Fig. 1. Position of Cueva de El Toro in the Antequera Mountains (Malaga, Andalusia) and its stratigraphic sequence, composed of distinct Neolithic occupation phases. This sequence consists of two Neolithic phases, Phase IV, and Phase III, with the latter being further divided into Subphases IIIA and IIIB. Between these Neolithic phases, there is a hiatus indicating a period of abandonment of the cave.

Thanks to the analyses applied to the materials and sediments from Cueva del Toro during the last decades, a considerable amount of new and fresh data have been provided about the social, cultural and economics behavirous of the Neolithic societies of the southern Iberian Peninsula. Through the examination of faunal remains and patterns of mortality and herd management, it was concluded that these occupations were primarily focused on livestock husbandry (Martín Socas et al. 2004; Navarrete et al., in press). These findings are also supported by functional studies of lithic tools, which reflect intensive work in activities such as butchery and processing of hides and leather. While the cutting of cereals (*sensu stricto*) was almost non-existent, the cutting of non-woody plants seems to have been more related to the gathering of plants other than cereals, perhaps for obtaining plant fibers used in basketry or textiles (Rodríguez et al. 1996). The exploitation of animal bones for crafting other tools of production, such as bone implements (awls, spatulas, needles, weapon points, etc.), was also documented. Tools made from durable animal materials like bones and marine mollusk shells have also been analyzed (Cuenca et al. 2011). Notably, mollusk shells were used as tools for smoothing the walls of ceramic bowls. However, the toolkit for working pottery was more diverse, as both bone spatulas and flint tool edges were employed for this purpose, as recorded in the Cueva del Toro itself (Rodríguez et al. 1996; Cuenca et al. 2021) and even instruments made from fragments of ceramic containers once amortized and fragmented. Additionally, analyses of fatty acids in ceramic vessels have documented the use of vegetable and animal fats (oils) – including suids and ovicaprids – and a particularly interesting discovery is the presence of dairy product residues (Tarifa et al. 2019). During the excavations, human remains were also recovered, shedding light on funerary practices and the presence of cannibalistic practices (Santana et al. 2019).

In this study, we present the results of the analysis of a specific type of tool – bone bipoints – from Level IIIb of the Cueva del Toro (Fig. 2). The levels in which they are documented present a chronological arc that develops between 4250 and 3950 cal BCE and corresponds temporally with other productive activities carried out at the site, such as ceramic production (Cuenca et al. 2011). Our main aim was to apply the traceological method (Semenov 1964) to observe the manufacturing and/or use marks. In addition, we combined traceological analysis with confocal microscopy to measure the observed use-wear traces on bi-pointed tools and quantitatively compare them with an experimental reference set. This approach aimed to determine the actual function of these tools and thus confirm or refute their initial hypothetical classification as projectile weapon points, as initially pointed out by D. Martín and colleagues in the monograph published in 2004. Here, the bipoints were described as ‘arrowheads’:

“… *aunque si conviene hacer hincapié en el incremento de los objetos dobleapuntados o* ***puntas de flecha****, no solo desde el ámbito cuantitativo sino, también, por el proceso seguido en su manufactura y la correspondencia morfométrica de los ejemplares conservados ya estén completos (fig. 105: 2-4) o fracturados (caso de la figura 105:6). Ambos aspectos, morfología biapuntada y métrica idéntica, son consecuencia de la* *elección del mismo soporte y técnica de fabricación. La extracción de varillas óseas a partir de dos cortes simétricos curvos unidos en ambos extremos, tradicionalmente asimilada al Paleolítico superior, permite la obtención de subproductos de gran fineza en sus dimensiones y que sólo requieren de alguna técnica complementaria para finalizar la elaboración, como el pulimento o el raspado. Asimismo destaca que en el último momento de su fabricación se realicen cortes transversales superficiales en la cara superior de la mitad inferior para facilitar su fijación al astil…* (Martín et al. 2004: 187).

[translation …*although it is convenient to emphasize the increase in double-pointed or* ***arrowheads****, not only from a quantitative perspective but also from the process followed in their manufacture and the morphometric correspondence of the preserved specimens, whether they are complete (fig. 105: 2-4) or broken (as in the case of figure 105:6). Both aspects, the bi-pointed morphology and the identical metrics, are a consequence of the choice of the same material and manufacturing technique. The extraction of bone rods from two symmetrical curved cuts joined at both ends, traditionally associated with the Upper Paleolithic, allows for the production of by-products with great fineness in their dimensions and only requires some complementary techniques to finish the elaboration, such as polishing or scraping. It is also noteworthy that in the final stage of their manufacture, superficial transverse cuts are made on the upper face of the lower half to facilitate their attachment to the shaft...*] (Martín et al. 2004: 187).

Fig. 2. Five of the six bone bipoints from Cueva del Toro (Layer IIIb). From 1 to 5 (TOR1, TOR2, TOR3, TOR4, TOR5). Notice the difference in wear between the distal area – indicating use – and the proximal

area – corresponding to the handle. Numbers 1 and 3 exhibit a higher degree of wear compared to the others.

Material and Methods

As stated above, the archaeological materials analysed and presented in this study consist of six bi-pointed bone splinters from Level IIIb of the Cueva del Toro (Fig. 2). Similar bi-pointed pieces have been identified in other sites in the region, such as Cueva de Huerta Anguita in the province of Córdoba (Gavilán 1986).

In an initial phase, macroscopic observation was employed for the analysis of the bi-pointed pieces, aided by a binocular magnifying glass (Olympus SZX7) (5-60x magnification). Subsequently, the microscopic traces were recorded and analysed using a Leica 2500M metallographic microscope (50-400x magnification). The field of view for this analysis varied, ranging from 5mm at the lowest magnification (50x) to approximately 0.45mm at the highest magnification (400x). In essence, we continued to employ the methodology established in previous studies, tailored for hard materials of animal origin, such as antler, ivory, and bone (Clemente-Conte et al. 2002, Clemente-Conte et al. 2010, Maigrot 2003, Lozovski et al. 2013).

The functional interpretation of the archaeological tools was undertaken with the support of the reference collection curated by the ADS group at the Milá y Fontanals Institution for Humanities Studies (IMF) within the Spanish Research Council (CSIC), which contains traces resulting from the work on various materials, including bark, wood, skin, non-woody plants, etc. The experimental collection of tools made from animal materials has been employed as a comparative reference in this study and in prior research (for example, Clemente et al. 2010). Earlier works on the processing and spinning of plant fibres and wool involved using lithic tools and mollusc shells to stretch fibres, as well as bone awls for weaving, pressing threads on a loom, and creating baskets (Clemente-Conte and Cuenca-Solana 2011). Experiments related to textile and basketry work have been also utilized for prior works on the textile technology at the early Neolithic settlement of La Draga (de Diego et al. 2017 & 2018). However, since the actions performed with these previous experimental tools did not precisely mirror those required for weaving and considering the differing shapes of the tools, we opted to extend our experimentation. We replicated four bi-pointed tools of similar size and shape to those archaeologically recovered from the Cueva del Toro. To manufacture them, bone rods of 10 cm in length were used, and then shaped by knapping and grinding with stone tools. All four were hafted into a wooden handle. A groove was made in the wood where the bipoint was inserted. In an attempt to mimic archaeological specimens, the longer part was left outside the handle (archaeological specimens have around 5 cm outside the handle, while approximately 4 cm remain inside the handle). Subsequently, the area closest to the handle was tied with a vegetal rope, and the same rope was used to apply pressure along the entire groove to secure the bone and prevent it from falling or detaching from the handle (refer to Figure 7). Two of them were utilized for weaving linen, while the remaining two were used for weaving wool.

In the second phase, both archaeological and experimental tools were measured using a Sensofar Plu Neox blue light scanning confocal microscope equipped with a 10x (0.30 NA) objective. The spatial sampling was set at 0.69 µm, with an optical resolution of 0.47 µm, and a z-step interval of 1 µm. The field of view (FOV) for these measurements was 2.2mm. We followed a protocol previously utilized by Ibáñez et al. (2019, 2021), Ibáñez & Mazzucco (2021), and Mazzucco et al. (2022). For each tool, between 12 and 24 zones of 650 × 500 µm has been measured using A EPI 20 × N (0.45 NA) objective, with spatial sampling of 0.83 µm, optical resolution of 0.31 µm, vertical resolution of 20 nm and a z-step interval of 1 µm. Then, subareas of 100 × 100 µm were selected from each zone using SensoMAP Standard v.8 from Digital Surf. Sampled subareas areas were processed using a levelling operator with a least squares (LS) plane method and a form removal operator. Spatial filtering is then applied to isolate the roughness components of the surfaces using a Gaussian filter with a 0.08 mm cut-off. Finally, 48 texture parameters included in the ISO 25178 standard and three parameters measuring the furrows contained in each surface have been extracted. Successively, we implemented an Rstudio script specifically made for the statistical analysis of textural data. The statistical procedure used in this study is made available on the TRAC3D repository (https://github.com/nmazzucco/TRAC3D/blob/main/BONETOOLS). The aim of integrating confocal microscopy in our analysis is to verify the outcomes of the qualitative use-wear analysis, based on visual trace observation, and to statistically assess the surface variability using textural parameters.

Results

Description of the Traces Observed in the Archaeological Materials

Of the five selected bone tools, only four were considered analysable. Tool number TOR4 was too affected by post-depositional alterations to be analysed from a microscopic point of view. Analysed tools were manufactured from bone rods of nearly 10 cm in length. Their tips were shaped through knapping and scraping with stone tools. The technological traces of this scraping are preserved on both the outer and inner surfaces of the bone's proximal end, which, due to this distribution, is assumed to have been the handle. On the rest of tools, a highly polished, shiny surface is present, covering at least 50% of the material. This polishing is evident on both faces of the tool and, as it becomes more developed, takes on an 'oily' appearance (Fig. 3). The lustre is most intense at the distal tip, whereas the mesial section still partially reveals the underlying technological wear. This enhanced polish development around the tip is associated with a more rounded profile of the entire surface, especially noticeable along the lateral edges, which transforms the initial cross-sectional shape of the tool. The opposite end of the tool appears much duller, with a rougher surface due to technological striations that predominantly align along the longitudinal axis of the tool. The transition between the polished and unpolished sections in the central part of the tool is very abrupt, appearing as a straight line (Fig. 3).

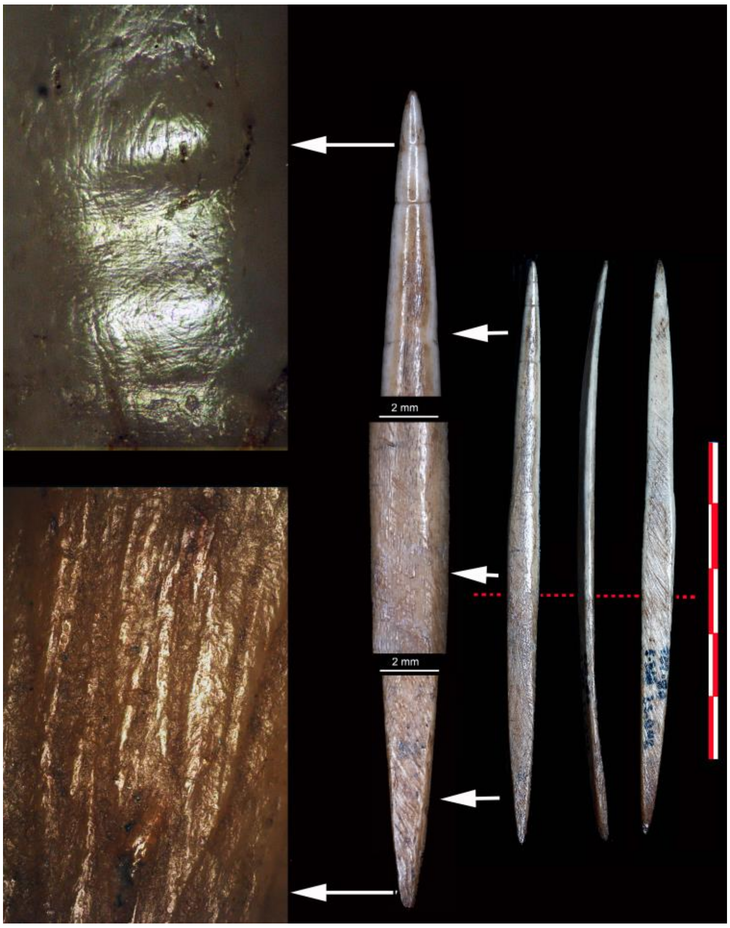


Fig. 3 – Tool no. TOR1. Difference in use traces between the distal part (use) and proximal part (hafted area). The red dashed line marks the boundary between both areas. Both photos at 100x.

At the microscopic level, the difference between the two surfaces is also quite pronounced. The non-polished or dull area, which we refer to as the proximal end, would have been inserted into a handle. The elevated areas in the microtopography, corresponding to the upper edges of the technological scraping marks, exhibit a polished texture with a compact, shiny appearance and few micro-striations or abrasions. We attribute this polished texture to contact with plant material from the handle (wood, reed, etc.) (Figs. 3:2, 4: 5, and 6).

The distal part is the active area of the tool, and the bright, oily-looking polish it exhibits is a result of use. Among the analysed tools, there are different degrees of utilization and, consequently, varying levels of trace development. Therefore, the broken tool in Figure 2: 5 and Figure 6, was fractured during use when the lateral edges had only just begun to blunt at the macroscopic level. However, it already displays an intense shine and a pronounced rounding of its surfaces at the microscopic level.

In general, among the tools with more developed traces, the polish is more compact in the distal part while being less striated (Fig. 6: 1 and 2). The predominant movement in the distal parts of the tools is longitudinal, while in the central and proximal sections of the active areas, we observe diagonally oriented striations primarily transverse to the longitudinal axis. (Fig. 6: 3; Fig. 4: 2 and 3; Fig. 5: 1 and 2). These differences indicate that the tool was used in complex movements rather than singular motions. With more intense uses, transversely oriented movements become clearer and affect a larger portion of the tool. The lateral edges become more rounded, while the distal part the tool thins out and takes on a more sinuous shape. Along these edges and on the external surface of the tool, a series of grooves with striations appear, oriented perpendicular to the longitudinal axis of the tool (Figs. 3 and 4). These grooves are related to significant friction and tension with the material being worked.

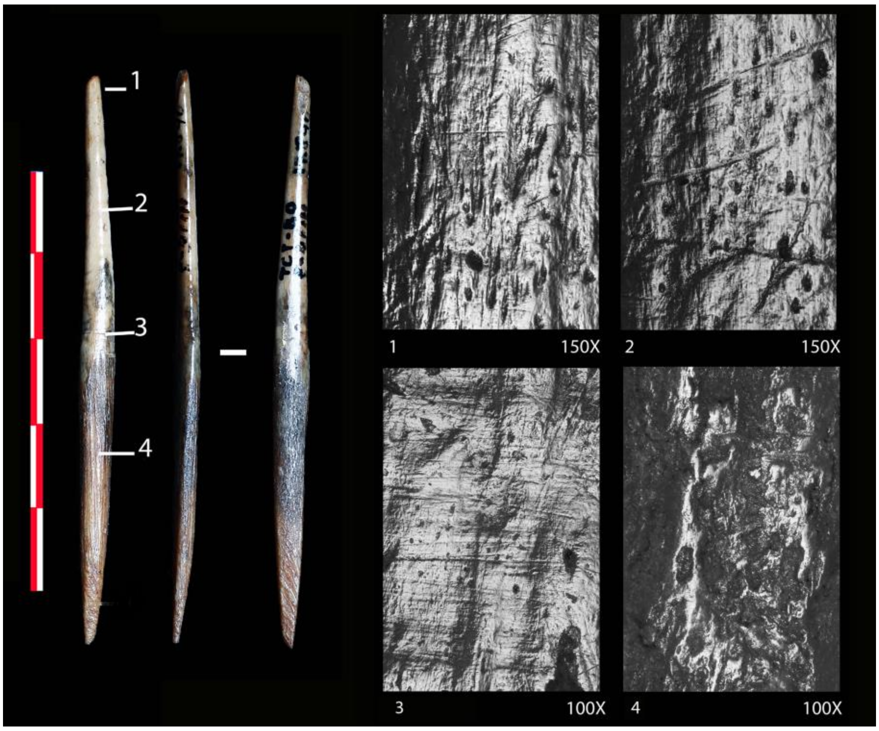


Fig. 4. Tool no. TOR3. Use-wear traces (1-3) and hafting wears on the proximal part (4).

Given the characteristics of the use-wear traces, we can reject the hypothesis of use as a projectile point. The rounded tips of the bi-pointed tools from Cueva del Toro do not match the macroscopic traces found on bi-pointed tools used experimentally as projectiles (see experimental references Pétillon et al., 2011; Bradfield & Lombard, 2011, among others). Basing on the observed use-wear traces, we believe that these tools were used for working fibrous materials. In certain aspects, such as the texture and polish of the wear patterns, there might be similarities with those observed on experimental tools used for woodworking (Clemente-Conte et al. 2002, Clemente-Conte and Lozovskaya 2011, Maigrot 2003, Maigrot et al. 2014). However, based on the documented gestures, the striations, the thickness of the polish, etc., we lean more towards the consideration of non-woody plant materials that are also abrasive due to the abundant presence of phytoliths (Legrand 2003 and 2008, Martial et al. 2013). Furthermore, the identification of probable fibre residues adhered to the surface of two cases (Fig. 5: 3) encourages us to interpret these tools as ‘needles’ used for processing/weaving fibres.

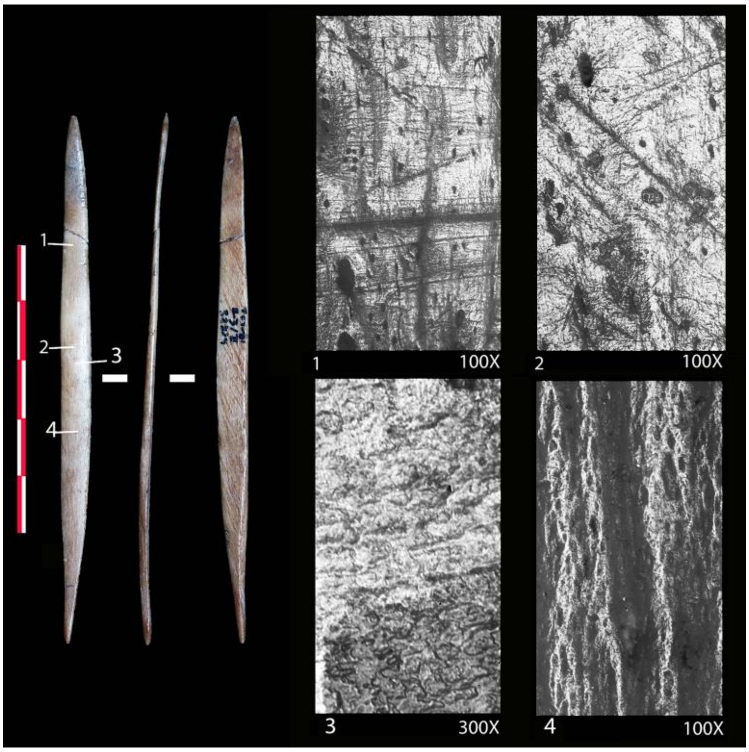


Fig. 5: 1 and 2 – Tool no. TOR2. Use marks due to contact with the woven material. 3: undetermined residue adhered to the needle’s surface, and 4: Use-wear traces due to the handle.

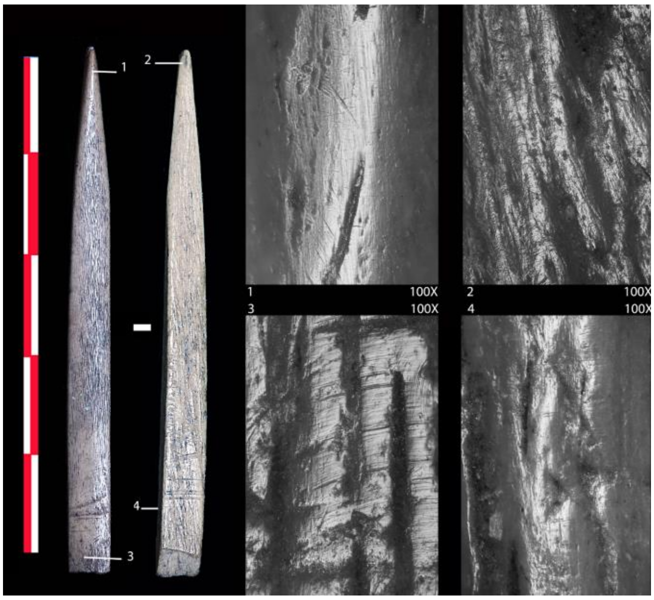


Fig. 6: Tool no. TOR5. Distal end of the needle used in some knitting activities as the rest of the bi-pointed tools.

Experimentation as a Referential Analytical Method

Experimental tools have been observed using both stereoscopic and reflected-light microscoy in order to highlight surface modification caused by use. We observed that the technical traces disappeared from the distal part due to contact with the processed fibres. This was not the case in the handle area, where the striations from the flint tool scraping were still visible. The bi-pointed tools were slightly blunted, and a shiny, compact polished texture developed on the contact surface. However, there were clear differences between the two types of fibres. The polished texture produced by contact with linen appeared flatter, while that from wool was more voluminous. The latter exhibited dark striations that looked like fine scratches, short and shallow, marking the movements of interweaving the fibres during weaving. In contrast, the striations resulting from weaving linen were deeper and longer, appearing as either light or dark markings with a wider 'U' shape. Furthermore, the 'micro-holes' and

ID	WORKED-MAT	TIME	ACTION	TOOL-TYPE	SPECIES	ZONES	SUBAREAS
H-EXP-1	UNUSED	0 MIN	NONE	AWL	Ovis aries	12	40
H-EXP-2	LINEN	60 HOURS	KNITTING	AWL	Ovis aries	18	60
H-EXP-3	LINEN	60 HOURS	KNITTING	AWL	Ovis aries	22	60
H-EXP-4	WHOOL	18 HOURS	KNITTING	AWL	Ovis aries	20	60
H-EXP-5	WHOOL	18 HOURS	KNITTING	AWL	Ovis aries	17	80
H-EXP-6	BARK	8200 DRILLS	PIERCING	AWL	Ovis aries	19	60
H-EXP-7	BARK	80 MIN	PIERCING	AWL	Alces alces	24	60
H-EXP-8	WHOOL	60 HOURS	KNITTING	AWL	Ovis aries	17	60
H-EXP-9	WHOOL	60 HOURS	KNITTING	AWL	Ovis aries	20	60

Tab. 1. Set of experimental tools used in this study and number of measured zones and subzones. EXP-6 and EXP-7 are part of the IMF's reference collection. The rest of experiments were made specifically for this research.

Depressions on the polished surface differed between the two types of fibres. In the case of linen, these features were larger, with irregular shapes and edges that weren't completely smoothed by polishing. On the other hand, in the case of wool, these features were much smaller, predominantly oval and/or circular in shape, with eroded edges, and in some instances, smoothed by polishing (Fig. 7).

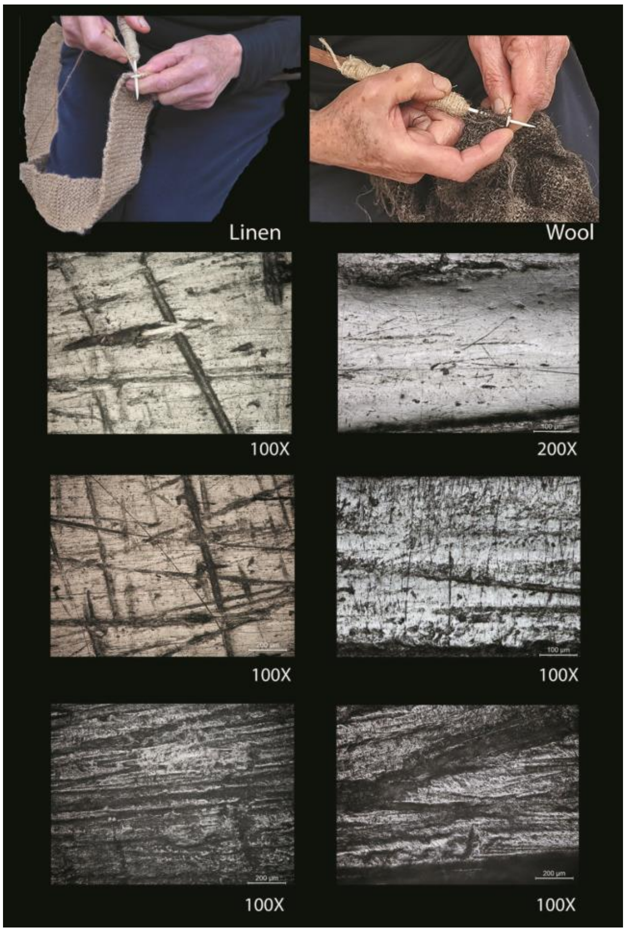


Fig. 7. Use-wear traces on experimental bi-pointed tools used for knitting linen – 18 hours (left column) and wool – 60 hours (right column). Pay attention to the contrast between the striations produced by each type of material and how the manufacturing technical traces are still preserved in the handle area (lower photos).

Quantitative discrimination through the confocal microscope

To create a quantitative reference library of use-wear traces from bone tools, we measured a set of experimental tools, one unused tool and six tools used for various working tasks: linen and wool crocheting, and birch bark drilling (Tab. 1). Measured data has been exported to Rstudio in .csv format (S1a). Dataset is then split into training and test sets based on the values in the CAT (1: Archaeological; 2: Experimental) column. This first training dataset contain all subareas from experimental tools separated into two categories (MAT2 column). The first group (1: TECN- surfaces with traces of manufacture only) contains subareas measured in the mesial and proximal part of the tool, thus related to manufacturing technical and handling traces, while the second category (2: USED - surfaces with use-wear traces) contains subzones from used areas. Before proceeding to the analysis, we run a data cleaning procedure. First of all, all rows containing null values are removed from the dataset, using functions 'sapply' and 'na.omit'. At this point, the list of numerical predictors is specified. 51 predictors are initially introduced. A test is made to eliminate predictors showing zero variance (i.e., constant columns) (S2). A correlation analysis is performed to identify and remove highly correlated predictors. P-values for each predictor are calculated using a correlation matrix (S3) and stored in a CSV file (S4). Predictors with p-values greater than 0.05 are identified and stored in a vector for potential removal (predictors_to_remove). Successively, a new correlation matrix is calculated for the updated predictors to identify and remove pairs of highly correlated predictors (correlation > 0.8) based on p-values from linear regression tests (S5). As result, seven predictors (Tab. 2) are stored in a vector called selected_variables and saved in a CSV file (S6). The cleaned and selected dataset is saved (S7). At this point, a Canonical Discriminant Analysis (CDA) is performed using the 'lda' function from the 'MASS' package. Discriminant scores are extracted and stored in a data frame; centroids for each class are calculated. The structure matrix, which contains contributions and coefficients for each variable in the CDA, is calculated and saved in a separated file (S7). The script calculates class centroids for each class based on the discriminant scores; coefficients are printed for each variable, showing their contributions to the discriminant functions (S8). At this point the CDA model is used to predict class labels for the training data, and the predictions are stored in the 'Prediction' column. Results are stored in a cross-table to compare the true class labels ('MAT2') with the predicted labels (S9). As results the 77.1% of subzones from technological and handling traces are correct classified and the 93.7% of subzones from used areas are correctly classified as USED. To further evaluate the accuracy of the classification a confusion matrix is computed (S10). Various evaluation metrics, including macro and micro averages of precision, recall, and F1-score, are calculated and printed. The classification accuracy is 91.1% for the logistic regression model. A density plot using first canonical discriminant function scores (LD1) is generated for visualization (Fig. 8, A).

The trained model is therefore used to perform a classification and generating predictions on the test dataset, including archaeological tools, using a trained Canonical Discriminant Analysis (CDA) model. Test data is cleaned, selecting the relevant variables, and ensuring that there are no missing values, following the same procedure as before. A blind classification is then made by applying the trained CDA model (cda_model) to the selected test data (selected_test_data). The discriminant scores (scores_blind) are extracted for each observation and the predicted class labels are added to the dataset (S11). As result, 98.2% of subzones from archaeological tools are classified among as used areas (Tab. 3). Classification can be visualized in the density plot created using the ggplot2 library (Fig. 8, B). To analyse the variation of parameters among different factors, a series of boxplots were created. Prior to generating these boxplots, potential outliers were removed from the dataset using a function named 'remove_outliers'. This function utilizes 'dplyr' package's functions such as filter for data manipulation to identify and exclude outliers based on the interquartile range method. Selected texture parameters (Smr2, Sbi, Sci, SWt, FurrowsMaxiumDepth, FurrowsAverageDepth) show a decrease in value from 'TECN' to 'USED', except of Svi (surface valley fluid retention) that measure the void volume of the deepest valleys below the core roughness (Fig. 9) (S23). This means that through use, bone surfaces go through a smoothing, with a reduction in roughness, groove density, and depth. The increase of Svi parameters can be interpreted as increase in the volume of valleys due to the smoothing of the overall surface.

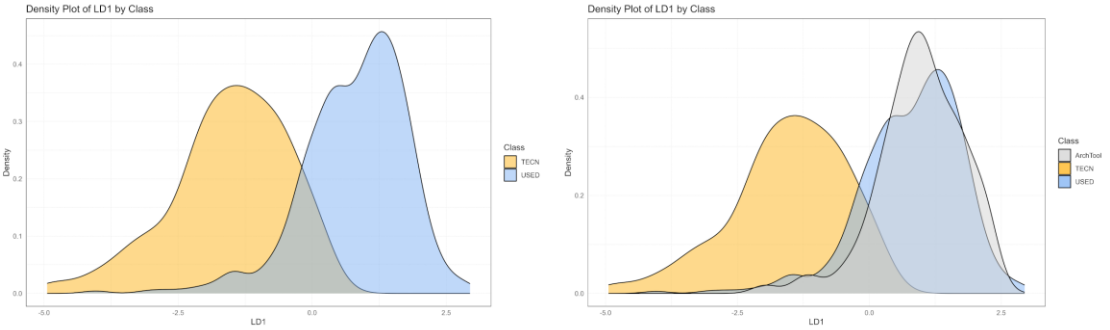


Fig. 8. Classification results from the Canonical Discriminant Analysis (CDA) for the two groups. It shows the distribution of LD1 scores for the training data (TECN, yellow; USED, blue) (A), and for the test data (B) (ArchTool, light grey).

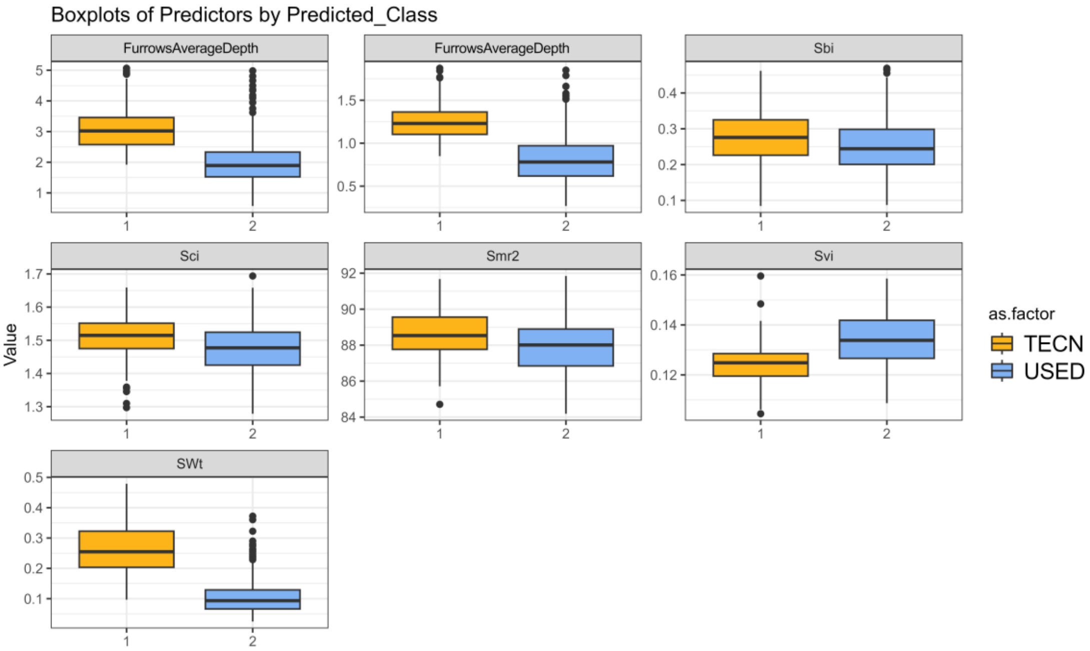


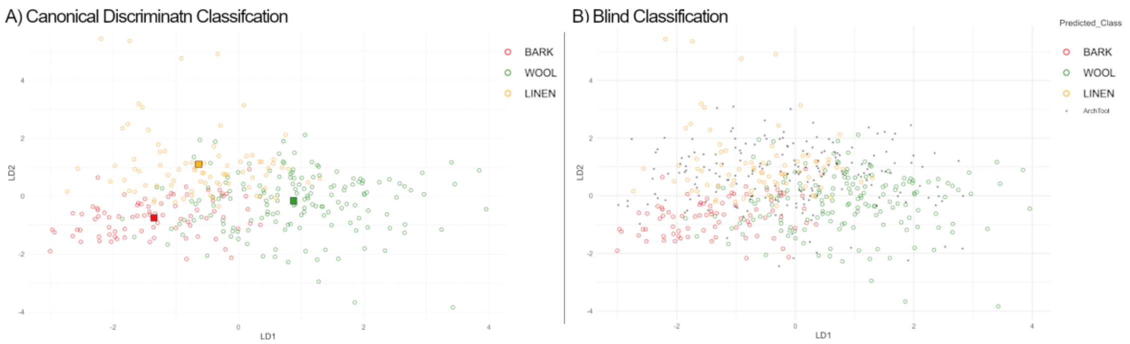
Fig. 9. Boxplot illustrating the distribution of selected numerical predictors categorized by the factor. Outliers have been removed for clearer visualization and better understanding of the central tendencies and variability within each category.

At this point, confirmed that archaeological tools are effectively classified as used, and that is effectively possible to well discriminate technological and handling traces from use-related modifications, we proceed to the discrimination of the worked materials, for three categories (‘1: Bark’, ‘2: Wool’, ‘3: Linen’). A new dataset is loaded (S1b), again split into two subsets: training_data2 and test_data2. First, the training set containing the data from experimental tools is analysed.

Cleaning procedures are carried out, removing missing values and filtering out predictors with zero variances. To reduce the number of predictors is select the most significant ones, p-values are obtained performing t-tests between each predictor and the target variable (MAT). Predictors with p-values greater than 0.05 are removed, as also highly correlated predictors (correlation > 0.8) to avoid multicollinearity (S12-S15). Nine selected predictors are finally selected (S16-S17). At this point, Canonical Discriminant Analysis (CDA) is performed to build a classification model (cda_model2). The coefficients for each variable are calculated (S18). Classification performance on the training data is evaluated by creating a confusion matrix, calculating accuracy, precision, recall, and F1 scores for each class. As results (S19), the 77.5% of subzones from tools that have worked Bark is correctly classified, the 87.8% of subzones from tools that have worked Wool is correctly classified, and the 58.8% of subzones from tools that have worked Linen is correctly classified. Classification results can be visualized on the scatter plot plotting by absolute values for LD1 and LD2 and group centroids (Fig. 10, A). Model accuracy is evaluated by estimating the global percentage of cases correctly Classified, that is 78.5% (S20).

One the trained CDA model is defined, we applied it to the archaeological dataset to predict class labels (S21) and calculate confidence percentages for each prediction. The script generates a scatter plot for the training and test data, combining known and predicted class labels (Fig. 10, B). Classification results at tool level can be visualized using a cross-tabulation, visualizing the classification of subzones for each analysed tool (S22). As result (Tab. 4), tool No. TOR2 is classified as having worked wool at 65%; tool No. TOR1 is classified as having worked wool at 57.5%; tool No. TOR3 is classified as having worked linen at 55%; tool No. TOR5 is classified as having worked Bark at 47.5% (Tab. 4). By looking at the variation of texture parameters variation between the three contact materials (Fig. 11) (S24), one can observe that: 1) Bark shows rougher surfaces, with more material at surface summits, highest peak density, better load-bearing capacity, and deeper furrows; 2) Wool: shows the smoothest surfaces, with the least material at surface summits, lowest peak density, but has slightly better valley fluid retention; 3) Linen shows and intermediate roughness, fewer surface summits than Bark but more than Wool, intermediate peak density, and the shallowest furrows.

Fig. 10. Classification results from the Canonical Discriminant Analysis (CDA) for the three groups. It shows the distribution of LD1 and LD2 scores for the training data (Bark: RED; Wool: GREEN; Linen: YELLOW) (A), and for the test data (B) (ArchTool, black dots).



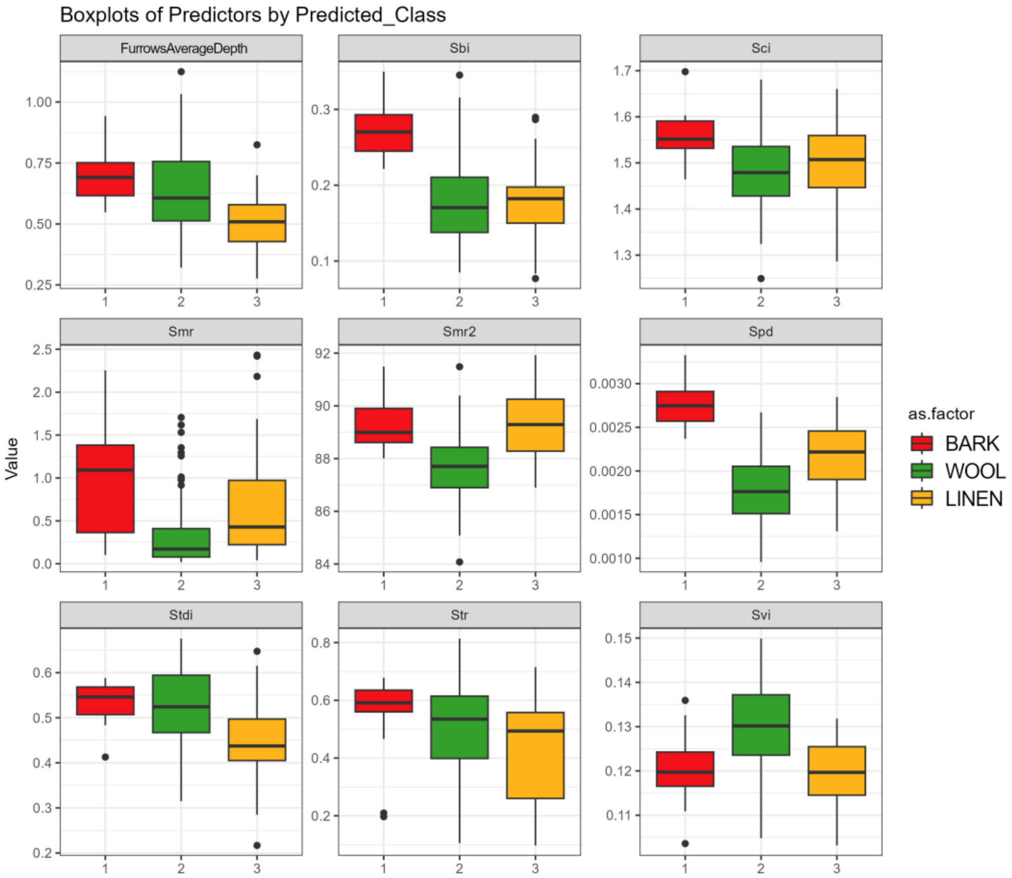


Fig. 11. Boxplot illustrating the distribution of selected numerical predictors categorized by the factor. Outliers have been removed for clearer visualization and better understanding of the central tendencies and variability within each category.

Discussion

The conducted study has brought forth several significant insights into the function and utilization of the bi-pointed bone tools discovered at the Late Neolithic site of Cueva del Toro. By applying traceological methods and employing both visual and quantitative analyses, a more comprehensive understanding of these tools' roles and their implications for the societal activities during that period can be discerned.

The primary departure point of the study was the morphological and typological classification of these bone tools as arrowheads (Martín et al. 2004). However, such an interpretation was refuted through the examination of macroscopic and microscopic use-wear traces. The key findings from this analysis indicate that these tools were not hunting implements, despite being probably equipped with handles, but rather played a role in crafting activities. The polished surface observed on these tools, covering a substantial portion of the material, is suggestive of their interaction with fibrous matter. This polishing, characterized by an ‘oily’ appearance, was notably evident on both faces of the tools. The abrupt transition between the polished and unpolished areas supports the notion that these tools were handled or hafted, making more realistic the hypothesis of their use for stretching and weaving fibres, such as wool or flax or similar materials.

The identification of use-wear traces associated with knitting activities at Cueva del Toro, strengthens the interpretation that the site’s inhabitants were engaged in textile production. This aligns with broader archaeological trends that highlight the importance of craft activities, including textile production, since Palaeolithic times, and considerably increasing during the Holocene (Romero-Brugués et al 2021; Mineo et al. 2023). However, in most of the sites characterized by dry conservation conditions, ancient craft of vegetal or animal origins are not preserved, and evidence of crafting activities must be sought in indirect proofs, such use-wear traces from working tools. These instruments reveal a portion of the productive activities required to achieve the final product, such as baskets, clothing, ropes, cordages of different king. In the case of awls and needles, they were likely used to create the textiles and then assemble the different pieces. Different tools, each suited for specific tasks, were essential components in transforming raw materials into finished products like textiles, highlighting the multifaceted skillset of the Neolithic societies.

This work affirms the significance of craft activities in the Late Neolithic levels of Cueva del Toro, as previously indicated by traceological studies on materials of various origins (Rodríguez et al. 1996; Tarifa et al. 2019; Cuenca et al. 2021; Camara et al. 2021). The presence of a diverse range of artifacts, including bone tools, pottery fragments, and faunal remains, suggests a multifaceted use of the site during Late Neolithic. The focus on craft activities, particularly related to the processing of fibres and animal materials, emerges as a significant aspect of the Level IIIb at Cueva del Toro. The study of the use-wear traces on bone tools contributes to our understanding of the specific roles these tools played in activities like weaving and fibre processing.

To better understand the type of weaving activities realised at Cueva del Toro, a further exploration of the type of fibrous material that may had been weaved has been made by including experimental tools (e.g., Martial et al. 2013) and analysing them by means of quantitative methods. The utilization of confocal microscopy to investigate polish variability on bone tools represents an innovative approach that enhances the credibility of functional interpretations. The application of quantitative methods to further explore polish variability on bone tools, represent one of the first attempts to apply confocal microscopy to this category of objects (Watson and Gleason 2016; Ma *et al.* 2023).

The experimental replication of weaving activities using similar bone tools, coupled with the subsequent analysis of use-wear traces, provided valuable comparative data. First, our pilot study allowed for a detailed exploration of use-wear polish, testing used areas against areas characterized by technological and handling wears. Use strongly affect the topography of the bone point, reducing the rugosity, and polishing the surfaces, resulting in an overall reduction of surface roughness.

Secondly, our study demonstrates that, thanks to a detailed experimental framework, it is also possible to quantitatively distinguish use-wear traces from similar contact materials (i.e., linen, bark, wool).

Of the four analysed tools, one has been classified has having most likely worked wool, as 65% of measured areas from this tool are classified together with the experimental tools used to knit wool. The close visual resemblance between the traces on tool No. 85/32824 and the experimental traces from wool weaving support this outcome. Observed use-wear traces on both archaeological and experimental tools show a rather smooth polish, but on which large pits and deep grooves are still visible.

Tools No. TOR1 and TOR3 are classified with more uncertainty. For tool No. TOR1, 57.5% of measured areas classified as ‘wool’, and the 42.5% is classified as having worked ‘linen’. The other way around, tool No. TOR3 show 55% of measured areas classified as ‘linen’, and 42.5% classified as wool. Such higher uncertainty in classification may be the results of several factors: 1) those tools may be used for knitting both materials, resulting in mixed use-wear patterns; 2) post depositional alternations may affect the interpretation of use-wear patterns; 3) the degree of use-wear development may also affect the interpretation of use-wear patterns. From a visual point of view, it is very difficult to distinguish use-wear from those tools. In both cases, use-wear polish shows rather smooth surfaces, densely pitted and striated, with only subtle differences (Figs. 1 and 3). Finally, the last tool shows an unclear classification between the three categories: with percentages of 47.5% of subzones attributed to bark drilling, 27.5 to ‘linen’ and 25 to ‘wool’. Visually, the polish on this element is rather rough, with grooves and striation. We can also wonder whether post depositional agents have may affected this tool.

These results highlight the complexity of distinguishing use-wear traces obtained from working fibrous materials on bone tools. It is possible that enlarging the experimental reference framework better results can be obtained. It is also possible that using a higher magnification and high numerical aperture (Calandra et al. 2019), better results can be obtained in the classification procedure, and this will be tested in the future.

Considering our archaeological analysis, it becomes evident that Late Neolithic communities displayed a remarkable diversity in the materials they employed for their weaving practices. While the utilization of flax and other plant-based fibres had been widely acknowledged in previous research (Mineo et al. 2023), our study has made a significant contribution by identifying evidence of wool weaving. This finding underscores the noteworthy initiation of sheep wool exploitation as a textile production material. Traditionally, the recognition of wool exploitation has been associated with sites dating back to the early to mid-third millennium BC, primarily due to the presence of textile remnants found in both the Eurasian region and Western Europe (Sherratt 1981). However, the exact origins of wool usage have remained somewhat obscure. Notably, our analysis sheds light on this intriguing aspect. It suggests an early utilization of wool at Cueva del Toro, occurring between 4250 and 3950 BCE, marking one of the earliest attestations of this practice. This discovery is particularly noteworthy in the context of the broader archaeological landscape. It is worth mentioning a remarkable case exemplified by the textile remains unearthed at the Novosvobornaya site in the northern Caucasus. This site, attributed to the Kurgan culture of the Bronze Age and dated between 3700 and 3200 cal BC, provides compelling evidence of wool’s integration with plant fibers, facilitating dyeing processes (Shishlina et al. 2003). Our analysis aligns with these broader historical narratives and contributes valuable insights into the early utilization of wool within ancient textile production practices.

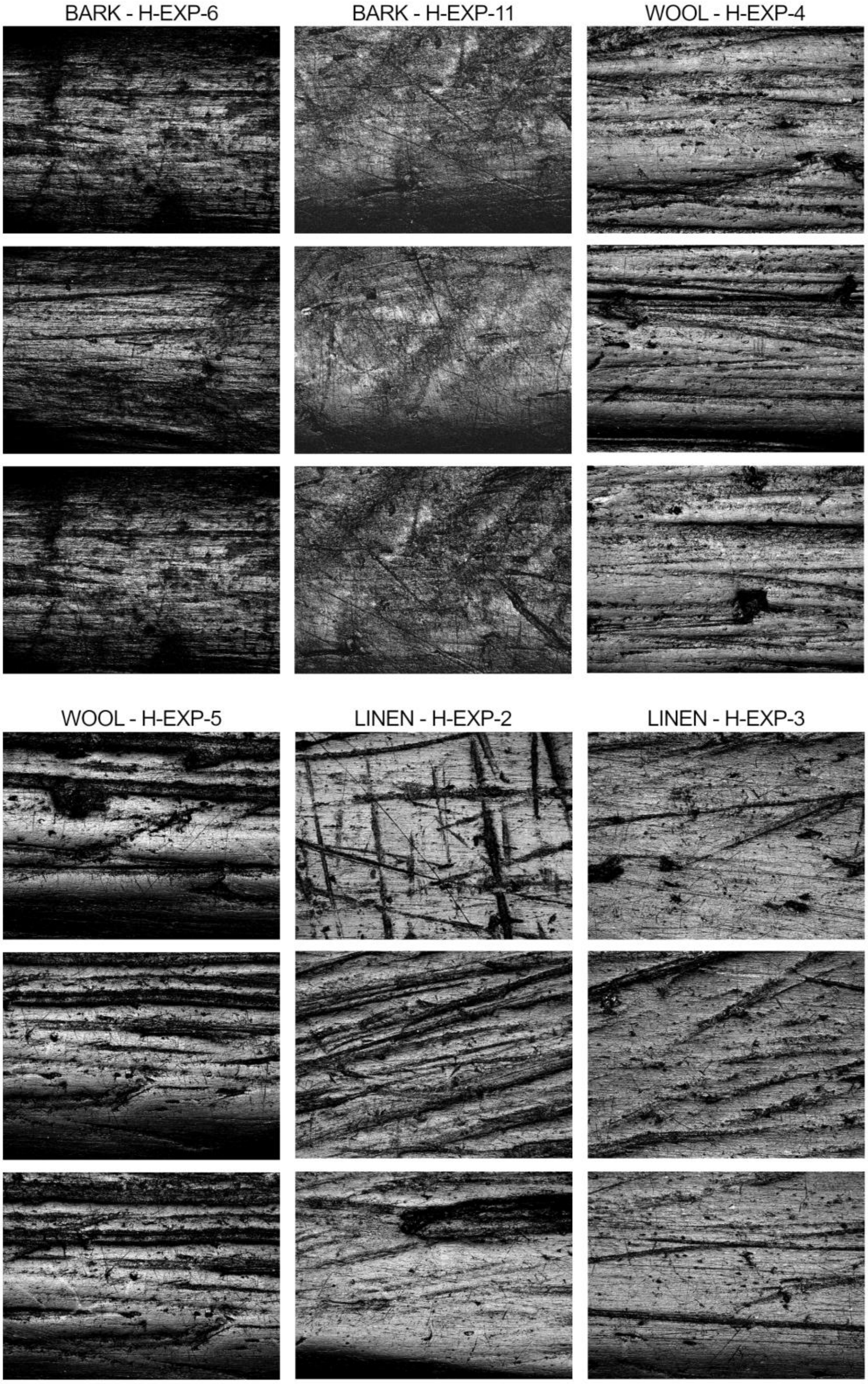


Fig. 12. Confocal stacks obtained at a total optical magnification of 100X using a S Neox 3D Profilometer. The imaging was performed with a 10X objective lens (0.3NA), The stacks were facilitated by SensoMap software.

Conclusions

The traceological assessment of bi-pointed bone tools from Cueva del Toro has yielded pivotal insights into the nature of craft activities during the Late Neolithic period. Through the employment of innovative methodologies and meticulous analyses, this research not only challenges prior interpretations but also establishes the significant role of these tools in weaving and fibre-processing tasks. Furthermore, by incorporating novel methods of analysis, this study contributes to the evolution of research techniques in use-wear analysis. The application of quantitative assessment using confocal microscopy has enabled the precise differentiation between used and unused areas. This approach has also enriched our comprehension of weaving-related traces. While parallels between use-wear marks from bark, linen, and wool activities are evident, this study approaches, for the first time, the tribological differences between them. Moreover, this investigation marks a foundational stride towards the establishment of quantitative reference libraries for use-wear traces. In subsequent studies, the expansion of experimental tools can potentially provide insights into the significance of working with vegetal fibres and the emergence of wool weaving. This study not only deepens our comprehension of Neolithic crafts, but also lays the groundwork for more deep investigations into past human activities and interactions with materials.

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