

Flint and quartzite: Distinguishing raw material through bone cut marks

Miguel Ángel Mate-González^{a,b}; José Yravedra^{c,d} David Manuel Martín-Perea^e; Juan Palomeque-González^c; María San-Juan-Blazquez^c; Verónica Estaca-Gómez^c; David Uribealraea^e; David Álvarez-Alonso^f; Felipe Cuartero^g; Diego González-Aguilera^b; Manuel Domínguez-Rodrigo^{c,d}

^a. Department of Cartography and Terrain Engineering, Polytechnic School of Avila, University of Salamanca, Hornos Caleros 50, 05003 Avila, Spain. mategonzalez@usal.es

^b. C.A.I. Arqueometry and Archaeological Analysis, Complutense University, Profesor Aranguren s/n, 28040 Madrid, Spain.

^c. Department of Prehistory, Complutense University, Profesor Aranguren s/n, 28040 Madrid, Spain. joyravedra@hotmail.com

^d. IDEA (Institute of Evolution in Africa), Origins Museum, Plaza de San Andrés 2, 28005 Madrid, Spain.

^e. Geodynamics Department, Complutense University of Madrid, José Antonio Novais 12, 28040 Madrid, Spain.

^f. Department of Prehistory, UNED. Madrid, Spain.

^g. Department of Archaeology, Autonomous University, Madrid, Spain.

Abstract

Since the 1980's several experimental analyses have been able to differentiate some lithic tool types and some of their raw materials according to the morphology of cut marks imprinted by such tools when used for butchering activities. Thus, metal tool use has been differentiated in contexts with an abundance of lithic tools, or even the use of hand axes has been documented in carcass processing in contrast with simple unretouched or retouched flakes. As important as this information is, there are still other important aspects to be analysed. Can cut marks produced with different lithic raw material types be differentiated? Can cut marks made with different types of the same raw material type be characterized and differentiated? The objective of this study is to evaluate if cut marks resulting from the use of different flints and different quartzites, are distinguishable from each other. In the present work, an experimental analysis of hundreds of cut marks produced by 5 types of flint and 5 varieties of quartzite was carried out. Microphotogrammetry and geometric-morphometric techniques were applied to analyse these cut marks. Results show flint cut marks and quartzite cut marks can be characterized at the assemblage level. Different types of flint produced cut marks which were not significantly different among them. Cut marks made with Olduvai Gorge quartzite were significantly different from those produced with a set comprising several other types of quartzites. Crystal size, larger in Olduvai Gorge quartzites (0.5 mm) than Spanish quartzites (177-250 µm), is discussed to be the main reason behind these statistically significant differences. This documented intra-sample and inter-sample variance does not hinder the resolution of the approach to differentiate between these two generic raw material types and opens the door for the application of this method in archaeological contexts.

Key Words: Raw materials, Flint, Quartzite, Cut Marks, Micro-Morphometry, Micro-Photogrammetry

Introduction

Traceology (i.e., use wear analysis) is a discipline that can allow the interpretation of lithic tool functionality (Semenov, 1964; Hayden, 1979; Keeley, 1980). However, it is frequent that preservation of the microscopic traces of tool use can be hindered by erosion, polishing, negligent laboratory treatments or the lithic record being exposed to biostratinomic (e.g., trampling) or diagenetic (e.g., chemical dissolution) modification processes. High resolution taphonomic analyses carried out on anthropogenic traces on bones found at archaeological sites can be a great addition and even alternative to these studies. The analysis of anthropologically modified bone surfaces can allow the recognition of the tools and raw materials used by ancient humans when processing animal remains for food, symbolic purposes or bone tool making.

Since the 1980's, some authors have been able to characterize and differentiate cut marks produced by different types of raw materials such as flint, quartzite, obsidian or metal (Olsen, 1988; Greenfield, 1999, 2004, 2006a, b; Dewbury and Russell, 2007; Bello and Soligo, 2008; Yravedra et al, 2009; Boschini and Crezzini, 2012; Mate-González et al, 2016), shells (Choi and Driwantoro, 2007), bamboo (Spennerman, 1990; West and Louys, 2007) or bone tools (Shipman and Rose, 1988; Hannus, 1990). Using these methods, authors such as Greenfield (1999, 2002, 2006) or Yravedra et al. (2009) have shown mammal defleshing was carried out using metal tools in periods where stone tools were most frequent, such as the Bronze Age. Other researchers have been able to determine whether cut marks were produced with different stone tool types such as simple, retouched flakes or handaxes, either experimentally (Walker, 1978; Bello et al, 2009; Domínguez-Rodrigo et al, 2009; De Juana et al, 2010) or in archaeological contexts (Shipman and Rose, 1983; Bello et al, 2009; Yravedra et al, 2011).

On previous studies, cut marks produced with Olduvai Gorge quartzites from the nearby Precambrian inselberg of Naibor Soit (Hay, 1976) have been compared to those generated by flint and basalt from the same region, showing morphometric differences between the three types of raw materials (Mate-González et al, 2016).

All these studies make use of different analysis techniques, including optic microscopy, hand lenses and scanning electron microscopy (SEM, Olsen, 1988; Greenfield, 1999, 2004, 2006 a, b), binocular microscope for high resolution pictures (Domínguez-Rodrigo et al, 2009; De Juana et al, 2010), three-dimensional reconstruction of cut marks made with 3D microscopy (Boschini and Crezzini, 2012), Alicona 3D Infinite Focus Imaging Microscope (Bello and Soligo, 2008; Bello et al., 2009) or using Micro-Photogrammetric and Micro-Morphometric analyses (Mate-González et al., 2016; Yravedra et al, 2016).

These studies have a potential problem when interpreting archaeological sites with an abundance of raw materials, such as those where it is common to find several types of flint, quartzite or volcanic rocks. Experimental analyses have shown the visible differences in cut marks produced by different raw materials such as flint, quartzite and

obsidian, but have not yet differentiated between different types of the same raw material.

In order to address this problem, an experimental study has been carried out to analyse cut marks produced by different types of flint and different types of quartzite. The main objective is to determine whether the resulting cut marks, made with different stone raw materials and different types of the same raw material, differ significantly one from another. The following hypotheses are proposed:

1. Cut marks made with different stone raw materials (flint and quartzite) differ one from another and can be classified and characterized. This would mean that data from different archaeological sites with different generic raw materials could be interpreted using experimental frameworks created by the use of the same type of generic raw materials, regardless of the source and their properties.

2. If tests carried out on cut marks produced with different types of flint show significant differences amongst them, and the intra-sample variance can be determined, this type of raw material could be identified solely by analyzing cut marks on bones.

3. If tests carried out on cut marks produced with different types of quartzite show significant differences amongst them, and the intra-sample variance can be determined, this type of raw material could be identified solely by analyzing cut marks on bones.

Materials and Methods

Materials

For this study, 317 cut marks produced with different types of flint and 255 cut marks produced with different types of quartzite have been analysed. Cut marks produced with flint come from a selection of different flint stones obtained in different areas: 33 from Vallecas (Madrid, Spain; Figure 1.A.A.), 33 from El Pedernoso 1 (Cuenca, Spain; Figure 1.A.B.), 35 from El Pedernoso 2 (Cuenca, Spain; Figure 1.A.C.), 27 from Manzanares (Madrid, Spain; Figure 1.A.D.) and 189 from Olduvai Gorge (Tanzania, Figure 1.A.E.). All flint samples are classified as nodular chert (Knauth, 1994), *with varying grain sizes from 0.5 to 20 μm* , but with consistent characteristics despite their different provenance.

Cut marks were also produced with quartzite from different regions: 29 from Segovia (Segovia, Spain; Figure 1.B.A.), 33 from Jarama (Madrid, Spain; Figure 1.B.B.), 27 from Yunquera de Henares (Guadalajara, Spain; Figure 1.B.C.), 34 from Río Cares (Asturias, Spain; Figure 1.B.D.), 25 from Río Cares 2 (Asturias, Spain; Figure 1.B.E.) and 107 from Olduvai Gorge (Tanzania, Figure 1.B.F.). Spanish quartzites presented quartz crystals with sizes from 177 to 250 μm , whereas the Tanzanian quartzite from Naibor Soit (Olduvai Gorge) showed 0.5 cm quartz crystals. Quartz in all

the samples ranges in colour from white and grey to black, forming a tight interlocking network.

Materials:

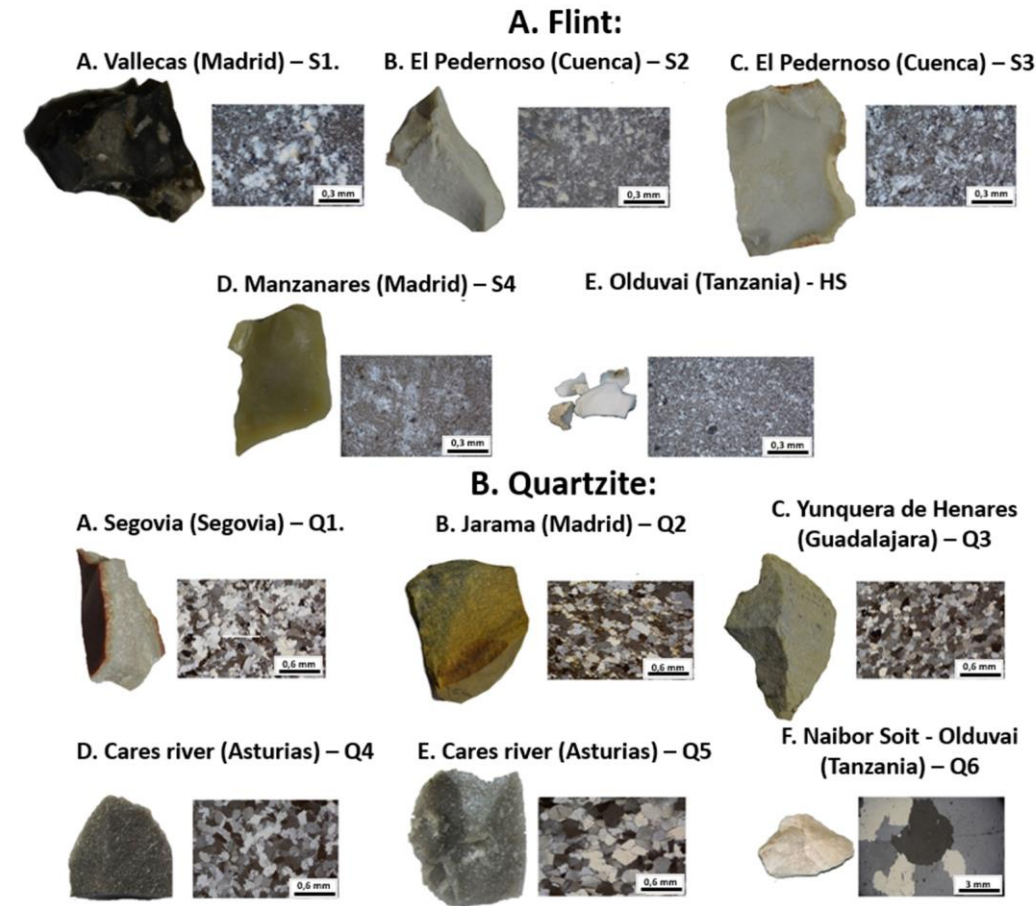


Figure 1. -> A. - Thin sections in cross-polarised light and photograph of studied flint samples. A. Vallecas flint (S1). B. El Pedernoso flint (S2). C. El Pedernoso 2 flint (S3). D. Manzanares flint (S4). E. Olduvai Gorge flint (HS). -> B. - Thin sections in cross-polarised light and photograph of studied flint samples. A. Segovia quartzite (Q1). B. Jarama quartzite (Q2). C. Yunquera de Henares quartzite (Q3). D. Río Cares 1 quartzite (Q4). E. Río Cares 2 quartzite (Q5). F. Olduvai Gorge quartzite (HC).

Methods

The analyzed cut marks were produced by a professional butcher when butchering long bones of young ovicaprids, using simple flakes made out of the different types of flint and quartzite studied in this experiment.

The method incorporates the treatment of high-resolution images obtained through micro-photogrammetry and computer vision techniques for the three-dimensional modelling of cut mark sections. Following the methodology of Maté-González et al. (2015), micro-photogrammetry was used to generate precise metrical models of cut marks when using images taken with oblique photography (Figure 2). It was proved that more stable and precise sensors captured better quality images, producing results that are more significant.

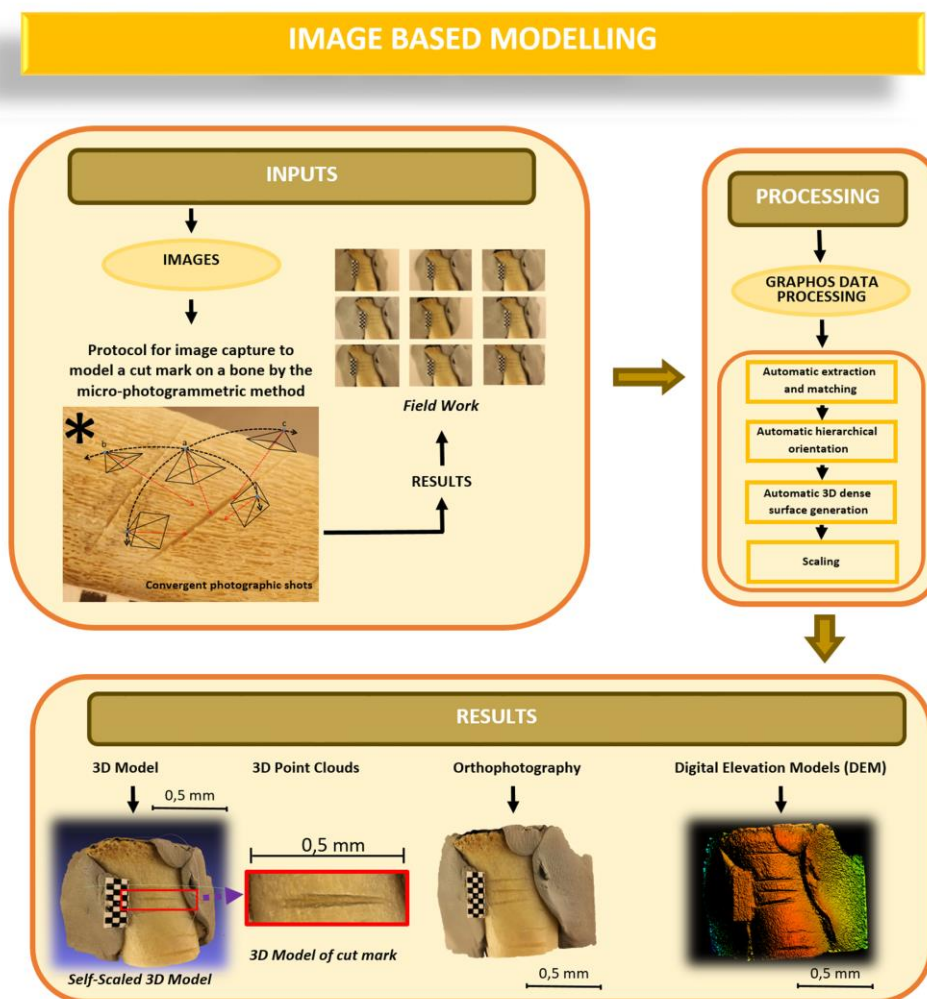


Figure 2. Workflow of the image-based modelling technique. * Protocol for image capture to model a cut mark on a bone by the micro photogrammetric method, with convergent photographic shots. A. Master and dependent images in central position B. Vertical slave images. C. Horizontal slave images.

Like in previous work, a **Canon EOS 700D** reflex camera was used, with a 60 mm macro lens, which obtained high resolution and high quality images (**Canon EOS 700D** => Type: CMOS; Sensor size: 22.3 x 14.9 mm²; Pixel size: 4.3 μm; Image size: 5184 x 3456 pixels; Total pixels: 18.0 MP; Focal length: 60 mm; Focused distance to object: 100 - 120 mm.). Specimens were individually placed on a photographic table with lighting adjusted to keep the bone permanently well illuminated. The photographic sensor had to be configured at the beginning of the process to adjust focus and brightness. A tripod was used to stabilize the camera during the photographic process. Both the exposition moment of the camera and lighting remained constant during the image data capture. The methodology required placing a millimetrical scale next to the cut mark to be photographed so as to provide a precise measurement reference.

Photographs were then taken following the specified protocol (Figure 2*). Once the photographs had been taken, they were processed to generate a 3D model for each mark. Consequently, the photographs were treated with a photogrammetric reconstruction software GRAPHOS (inteGRated PHOtogrammetric Suite, Figure 2,

González-Aguilera et al., 2016a, 2016b) and other reconstruction software such as Agisoft PhotoScan, PIX4D or PW (González-Aguilera et al., 2013). After producing scaled 3D models, Global Mapper software was used to define and measure mark profiles (Figure 3). For data collection, a total of 6-9 photos are taken for each mark. The number of photos varies depending on the geometry of the bone and the shape of the mark. The three-dimensional reconstruction of each mark takes 30-40 minutes depending on the final number of photos taken.

Our goal with the reconstructions is to maximize both accuracy and completeness. If the separation among images (baseline) increases, the accuracy will improve as the intersection of the perspective rays is more favorable, but the completeness of the object decreases due to the dense cloud algorithms. By contrast, if the separation among images (baseline) decreases, a better completeness of the object will be obtained, but the accuracy will be poorer because of a worse intersection of the perspective rays.

In order to contextualize the accuracy analysis of Photogrammetry and Geoinformatics (PG) methods vs. microscopy given that geometric data are dependent from two different sources (scaling and photogrammetric reconstruction-PHO), the variance of the PG could be estimated as follows:

$$\sigma_{PG} = \pm \sqrt{(\sigma_{scaling} \cdot GSD)^2 + (e_{PHO} \cdot GSD)^2} \quad (1)$$

where, $\sigma_{scaling}$ is the scaling precision established as 1/3 of the pixel (Luhman et al, 2013), e_{PHO} is the re-projection error of the photogrammetric bundle block adjustment expressed in pixels and GSD is the ground sample distance expressed in m/pixel. In this way, it is possible to obtain a comprehensive and complete comparison, at geometric and statistical level.

Cut marks were measured at mid-length (about 50% of the mark length) as suggested in Maté-González et al. (2015). According to such description, the confidence range to measure the marks hardly varies if they were between 30% and 70% of the mark length (Figure 3.A.).

A series of measurements including WIS, WIM, WIB, OA, D, LDC, RDC (sensu Bello et al., 2013) were made on the mark section (Figure 3.B.) and were taken as quantitative variables. The measurements for each mark section were later compared using the Pandora library (Palomeque-González et al., 2016). Pandora is a specific program created in R for the analysis of cut marks. Pandora automatically analyses cut marks from a statistical and morphometric perspective. This method facilitates a fast analysis of a large number of variables and samples. ANOVA, MANOVA and Principal Components Analysis (PCA) tests are carried out using the R freeware (Core, 2016). ANOVA tests consist of a variance analysis of each variable separating the marks by raw material and comparing two different groups. MANOVA tests are similar to ANOVA tests but use more than one variable at the same time to make the comparison.

This test can be applied with all variables at the same time or only with those which result statistically more significant in ANOVA tests. The application of ANOVA required a previous use of Bartlett's test in order to confirm that variance was homogeneous throughout the sample. The PCA estimates similarities and differences of marks on a two-dimensional Euclidean space and in the present study the raw measurements transformed through scaling were used. Plotting of the PCA results with confidence ellipses was made according to Wickham (2009).

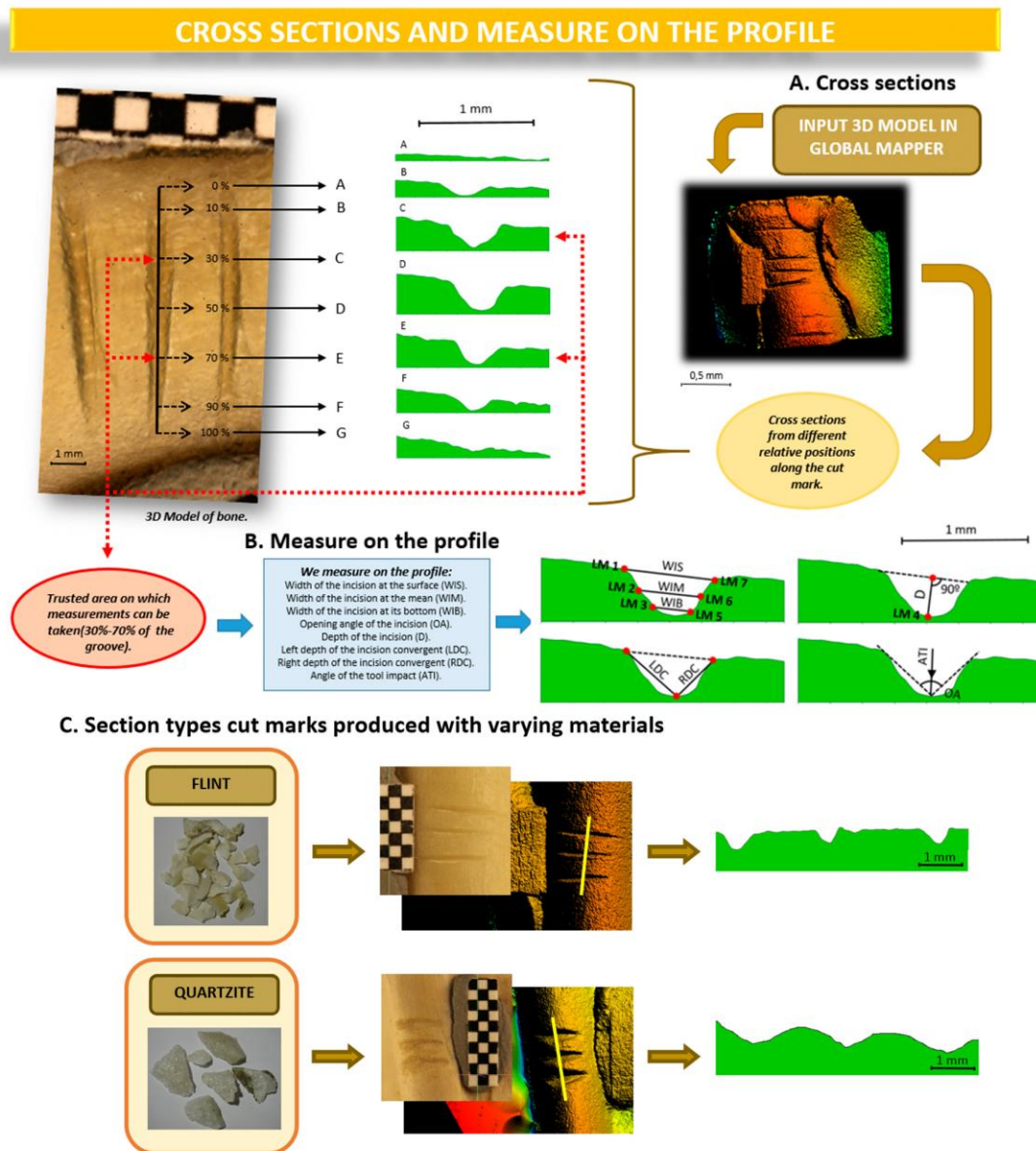


Figure 3. -> A. - Representation of the a-g sections of the cut mark regarding its length. -> B. - Location of measurements sensu Bello et al. (2013). Landmarks (LM1-7) used for the morphometric model are also represented. -> C. - Cut marks generated with a quartzite and flint flake. Detail for the V sections in the both types of cut marks.

A geometric morphometric analysis was performed along with a Generalized Procrustes Analysis (GPA) as a complement to the multivariate metric analysis (Figure 3.B.). In this case, a morphometric analysis approach was taken based on seven

identical landmarks per section, as shown in Figure 3.B. (LM 1-7), which were considered from each mark using the tpsUtil (v. 1.60.) and tpsDig2 (v.2.1.7) programs (Rohlf, 2015), following Maté-González et al, (2015).

In geometric morphometrics, a landmark point is a point in a shape object in which correspondences between and within populations of shape objects are preserved regardless of allometric differences caused by size. In the present study, the location of seven landmarks respond to the measurements considered for the statistical analysis, as seen in Figure 3.B (Maté-González et al., 2015). LandMark 1 (LM) was located at the beginning of the groove in the mark section. LM2, was located in the middle of the groove. LM3 was placed approximately at 10% of the end of the mark. LM4 was at the very end, and LM5, LM6 and LM7, in an opposed position to LM3, LM2 and LM1, (Figure 3.B.) (see also Maté-González et al [2015] for a more comprehensive description of these variables). These landmarks are identical in their properties (i.e., they reproduce the groove section using the same variables at different points of the groove trajectory). The resulting tps file was imported to R and analysed via the “geomorph” library (Adams and Otárola-Castillo, 2013; Sherratt, 2014).

Subsequently, a general Procrustes analysis (GPA) was applied on the landmark data, followed by a PCA (see Figures LM1-7 in Figure 3.B.). Morphometric disparity analysis was possible by using the morphol.disparity function, which estimated the group distances via the diagonal sum of the covariance matrix (Zelditch et al., 2012). The relativization of the allometric divergences of objects caused by disparities in their sizes when applying a GPA allows to compare objects strictly by their shape. This is achieved by an algorithm that after random selection of one shape, will superimpose subsequent shapes according to landmark locations. Then, computation of the mean shape of the sample or population of shapes is carried out. The algorithm then evaluates the distance between the original and the superimposed shape and adjusts for the whole sample with regards to the mean shape. GPA translates, rotates and uniformly scales objects in an optimum way.

Lastly, a Linear Discriminant Analysis (LDA) was performed to estimate the differences among the several groups of marks defined by raw materials. The LDA function included in the MASS R package was used (Venables and Ripley, 2002). The LDA allowed the elaboration of confusion matrices to evaluate the accuracy in group classification.

Results

The models developed through the micro-photogrammetric method are based on oblique photography and use a reflex camera with a macro lens, generating high quality 3D models of cut marks on bone (average GSD (mm) = ± 0.0078 ; average scaling error (mm) = ± 0.0157 ; average precision (mm) = ± 0.0238). This method fulfills the requirements of quick capture, automatic processing of images and accuracy assessment (Mate-González et al., 2015).

From a qualitative perspective, Figure 3.C. shows that cut marks made with flint and quartzite (regardless of the internal variance of both types of raw material) had commonly a V section, but the cut marks made with flint were narrower and deeper than the ones made with quartzite (Figure 3.A.). These results were similar to the ones observed previously, where flint and quartzite showed differences in shape (Walker 1978; Mate-González et al, 2016).

ANOVA and MANOVA tests measuring raw metrics show important differences between flint and quartzite (Figure 4). These affect mostly to the following variables: WIS, WIB, WIM, SI, D, and OA.

	Difference F-Q (All Quartzites)	Difference F-Q (Without Olduvai Quartzite)
ANOVA WIS	3.563×10^{-16}	1.833×10^{-23}
ANOVA WIM	2.405×10^{-24}	7.834×10^{-32}
ANOVA WIB	7.284×10^{-30}	2.776×10^{-33}
ANOVA SI	3.485×10^{-2}	1.282×10^{-2}
ANOVA D	3.168×10^{-3}	1.545×10^{-15}
ANOVA OA	3.902×10^{-8}	5.037×10^{-1}
MANOVA	8.393×10^{-40}	4.112×10^{-32}

Figure 4. Result of Anova and Manova test.

A PCA using the most discriminant variables was carried out to compare the cut marks made with both raw material types (Figure 5.A.). The 95% confidence ellipses of the PCA of the measurements specified in Figure 3.B show the dimensional differences between quartzite and flint cut marks, despite the strong overlap of some of them (Figure 5.A.). In this experimental sample, when distributing cut marks according to the two types of raw material, raw measurements showed overall larger dimensions of the variables in cut marks made with quartzite, which enable a correct classification of 69% of marks according to raw material type (Figure 5C).

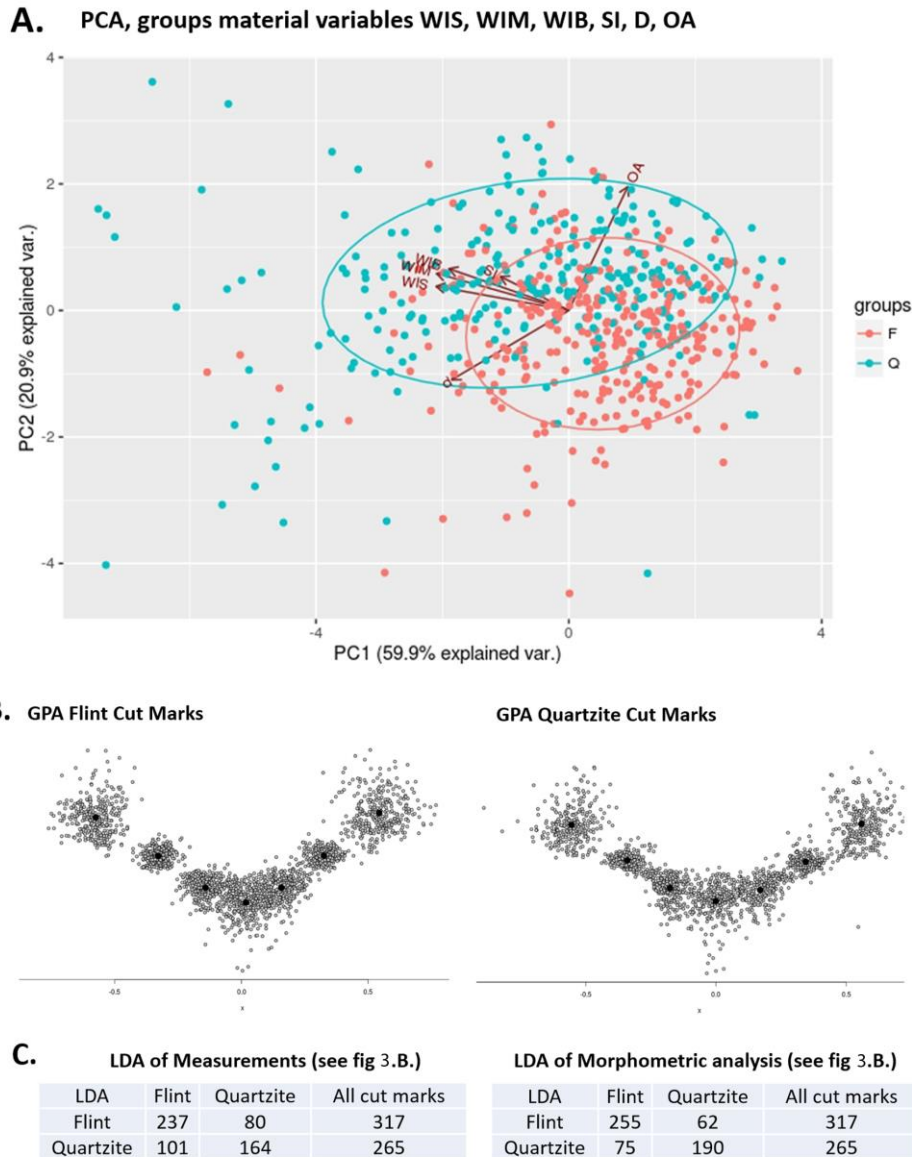


Figure 5. -> A. - Principal Components Analysis (PCA) of cut marks produced with flint (F) and quartzite (Q) tools. -> B. - GPA test Silhouettes of cut marks produced with flint (A) and quartzite flakes (B). The black points are the centroids associated to each landmark. -> C. - DLA (Discriminate Lineal Analysis) of measurements and morphometric analysis for flint and quartzite cut marks showing the number of correctly classified marks (diagonal) and those that were incorrectly classified according to flint or quartzite (out of diagonal).

The geometric morphometric two-dimensional analysis of the seven landmarks discards differences caused by dimensional variables and focuses on shape distances (Figure 5.B.). According to this analysis, quartzite cut marks are more open and shallower than those inflicted by flint tools. Shape distances enable a correct classification of as many as 76.5% all the cut marks (Figure 5C).

These results agree with previous comparative experiments of marks made with flint or quartzite (Walker, 1978 and Mate-González et al., 2016), proving that in a high

number of cases it is possible to distinguish between quartzite and flint used in butchery.

The analysis of internal variance of each raw material group shows interesting results too. In regards to cut marks made with flint flakes, the analysis shows a similar pattern of cut mark sizes and morphology regardless of the different flint types. The PCA (Figure 6.A.) produced with Vallecas, El Pedernoso, Manzanares, and Olduvai flint flakes do not show significant differences between the resulting cut marks with a strong overlap of the 95% confidence ellipses and a dense cloud with limited point scatter.

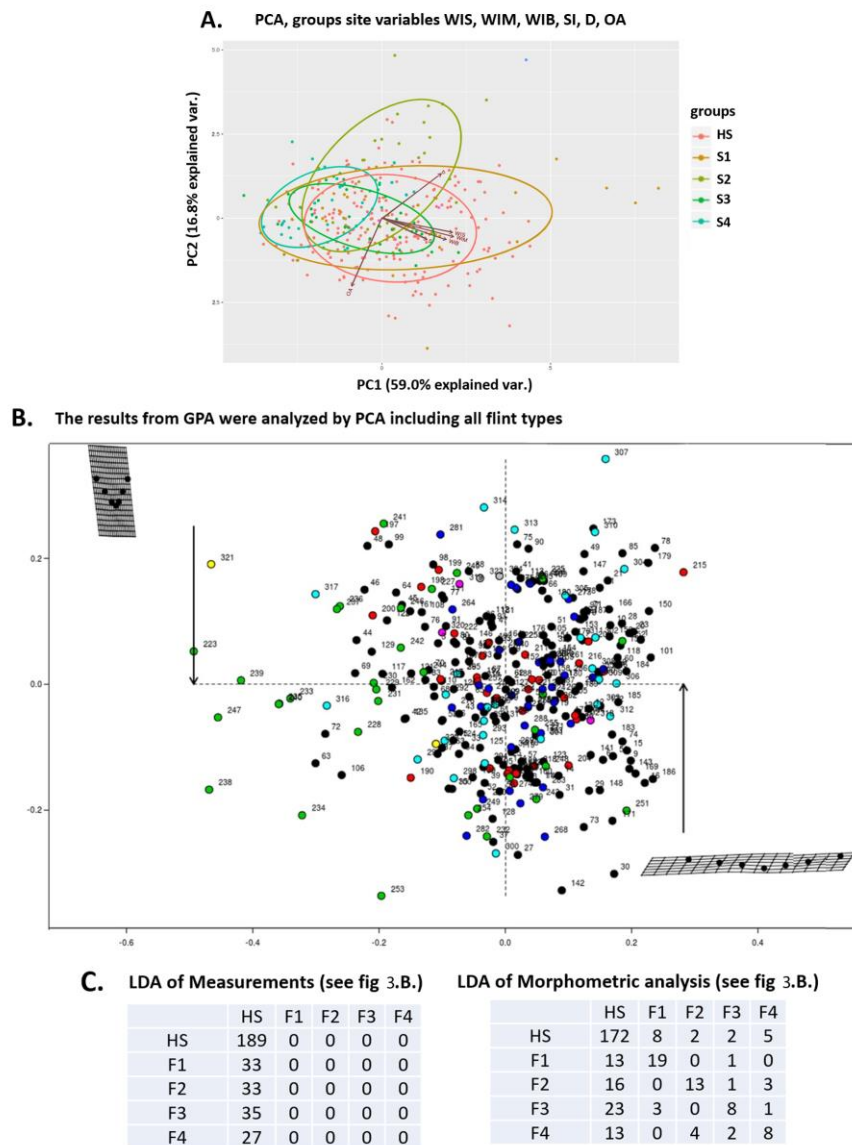


Figure 6. -> A. - Principal Components Analysis (PCA) of cut marks produced with different flint tools (F). -> B. - PCA of the GPA with the cut marks made with different flint flakes. -> C. - DLA (Discriminate Linear Analysis) of measurements and morphometric analysis for Vallecas (F1), El Pedernoso 1 (F2), El Pedernoso 2 (F3), Manzanares (F4) and Olduvai (HS) cut marks showing the number of correctly classified marks (diagonal) and those that were incorrectly classified according to flint type (out of diagonal).

The LDA of measurements include all cut marks made with flint, including Olduvai Gorge flint (HS, Figure 6.C.). As can be seen, the different flint cut marks cannot be differentiated correctly (Figure 6.C.). The LDA shows that four of the five flint groups do not get any mark made with flakes correctly classified. Cut marks produced by different types of flint flakes are very similar dimensionally and, therefore, difficult to differentiate one from another.

Regarding the GPA, most mark shapes are also very similar, although some morphological variability is recorded (Figure 6.B.). A confusion matrix shows that 69% of marks are correctly classified according to flint type (Figure 6C). Therefore, it is safe to say that cut marks produced by different types of flint show a range of shape variance that is large enough to allow some within-sample classification, but not enough to be mostly confused with quartzite cut marks (see below).

Quartzite cut mark properties describe two different situations. When all cut marks, including the cut marks made with Olduvai quartzite, are analysed, several differences between cut marks made with Spanish quartzite flakes and those from Olduvai Gorge can be documented. The PCA (Figure 7.A.) produced with Segovia (Q1), Jarama (Q2), Yunque de Henares (Q3), Río Cares 1 (Q4), Río Cares 2 (Q5) and Olduvai Gorge (HC) quartzites display some clear differences. Spanish quartzites appear grouped with their ellipses showing intense overlap. A PCA of the cut marks made with Spanish quartzites reveals homogeneous results within the group, making cut marks made with any of them undistinguishable from another in terms of their overall dimensions (Figure 7.B.).

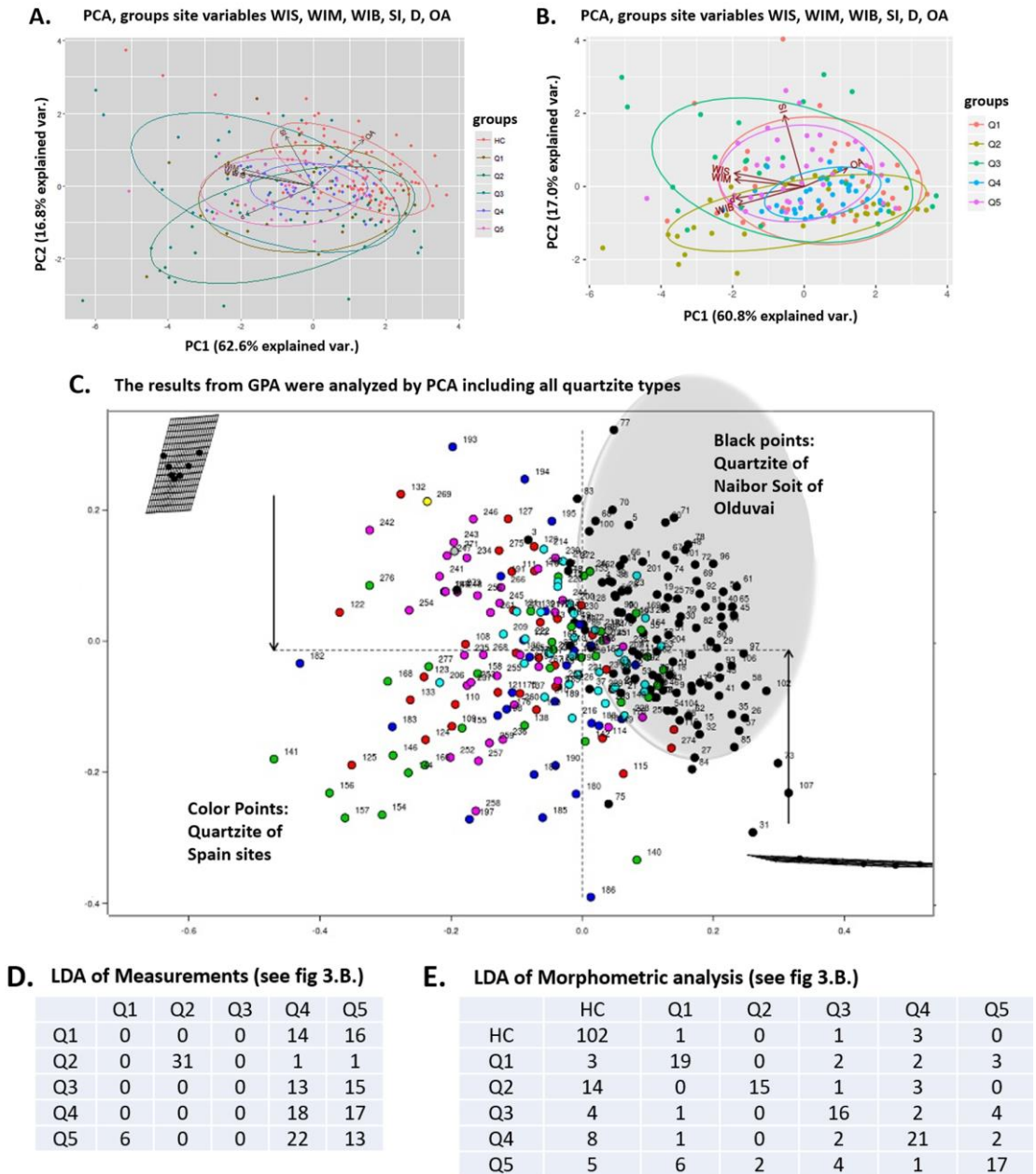


Figure 7. -> A. - Principal Components Analysis (PCA) of cut marks produced with different quartzite tools. Including Olduvai Gorge quartzites (HC). -> B. - Principal Components Analysis (PCA) of cut marks produced with different quartzite tools. Including only Spanish quartzites. -> C. - PCA of the GPA with the cut marks made with different quartzite flakes. -> D. - DLA (Discriminate Linear Analysis) of morphometric analysis for Segovia (Q1), Jarama (Q2), Yunquera de Henares (Q3), Cares river 1 (Q4), Cares river 2 (Q5) and Olduvai Gorge (HC) quartzite cut marks showing the number of correctly classified marks (diagonal) and those that were incorrectly classified according to flint type (out of diagonal). -> E. - DLA (Discriminate Lineal Analysis) of morphometric analysis for quartzite of Segovia (Q1), Jarama (Q2), Yunquera de Henares (Q3), Cares river (Q4) and Other Cares river (Q5), cut marks showing the number of correctly classified marks (diagonal) and those that were incorrectly classified according to flint type.

The confusion matrix resulting from the GPA shows that 95% of Olduvai Gorge quartzite cut marks are correctly classified, but Spanish quartzite cut marks show only 65% of Q1, 46% of Q2, 59% of Q3, 61% of Q4 and 49% of Q5 marks correctly classified (Figure 7.C.).

When a metric LDA is made, excluding the Olduvai Gorge quartzites, it can be observed that the correspondence between quartzites is very homogenous, making it difficult to correctly classify them. This similarity is such that Q4 is only correctly identified 40% of the time whilst Q5 only 45% (Figure 7.D.). In contrast, Q2 cut marks were correctly classified 92% of the time. A confusion matrix shows that only 37% of marks can be correctly classified according to quartzite type (Figure 7.D.).

The results from GPA were analyzed by PCA including all quartzite types (Figure 7.C.). All the points representing cut marks produced with the different quartzites were clustered in two independent groups, Olduvai quartzite (black dots) and the rest of the Spanish quartzites (coloured dots). These results suggest two different profiles: one with very similar cut marks, produced by analogous quartzites, and another with Olduvai Gorge quartzite, different from the rest (Figure 7.C.). A confusion matrix resulting from the LDA shows that, in contrast to metric variables, shape distances can correctly classify 71.6% of all marks. This shows a far broader within-sample variance when comparing cut marks made with quartzite with those made with flint, probably reflecting a substantially wider variability in raw material quality in the former, as reflected by much more diverse metric and morphological measurements and distances.

It is possible that these differences rely solely on the contrasting crystal sizes shown by these two groups of quartzites. Thin sections carried out on all samples showed Olduvai Gorge quartzites were composed of 0.5 cm crystals, compared to the significantly smaller crystals with sizes between 177 and 250 μm found in Spanish quartzites. Olduvai Gorge quartzites, due to their petrological and mineralogical characteristics, have misled some authors to classifying them as quartz (Sánchez-Yustos, 2012; Santonja et al, 2014). This is undoubtedly due to the type of crystallization these quartzites show, behaving similarly to quartz.

Discussion

The combined dimensional and geometric-morphometric approach in the study of cut marks comparing marks created by flakes from structurally different raw materials can yield potentially discriminating results leading to classification of cut-marked assemblages to specific types of raw material effectors. This should never be understood as a direct relationship between single cut mark morphological properties and specific effector type. The analysis here shown contains a moderate to high degree of correct classification, especially when strictly morphometric variables are considered (via GPA). Cut marks made with flint and quartzite can be correctly identified in the experimental assemblage in 76.5% of cases.

The limited degree of accuracy achieved is because intra-sample variability comprises a substantial amount of variance due to the diverse properties of different types of flint and quartzite used. The initial goal was to assess if such an intra-sample variance according to each of the two types of raw material could bias interpretations enough to make the differentiation of cut marks resulting from the use of flint or quartzite flakes very unreliable. This hypothesis can be rejected at the assemblage level. When such a high internal variance intra-sample is shown, the morphological properties of cut marks can still be informative enough to correctly discriminate 3 out of every 4 cut marks linking them to raw material type using the same type of effector. In every single stage of this analysis, we have shown that morphometric properties of marks are more important than dimensional ones to differentiate mark and raw material types.

These positive results enable the next stage of research, namely the application of this type of study to cut marks from the fossil record, to be feasible. Taphonomists could potentially study the dimensional and morphological properties of cut marks of any given assemblage and attempt to interpret them according to the raw material represented in the cutting tools documented at the same assemblage. This would require the creation of experimental analogues using exactly the same type of raw materials prior to any attempt to correctly classify the cut marks. This is crucial given the intra-sample variance documented here given that all generic rock types (i.e., quartzite) are not the same and their granulometric properties influence overall cut mark morphology and size.

Conclusions

In conclusion, and regarding the initial hypotheses proposed at the start of this study, the following can be determined:

1. Cut marks made with different raw materials, such as flint and quartzite, can be differentiated at the assemblage level. Although this is no novelty, since other authors have already made similar observations (Walker, 1978; Fernández-Jalvo et al., 1999; Yravedra, 2006; Maté-González et al., 2016), the present study has documented that such is the case. This may be due to the wider sample studied, including 317 flint produced cut marks and 255 quartzite produced cut marks, as well as to the methodology used. The geometric morphometric method, following Mate-González et al. (2015) allows wide samples to be used and to obtain good statistically-supported classificatory results.

2. Analyses on cut marks produced with different types of flint do not show significant differences amongst them. It is possible that the use of more sophisticated cut mark analysis techniques, such as the use of 3D-Microscopy (Boschin and Crezzini, 2012), or an Alicona 3D Infinite Focus Imaging Microscope (Bello and Soligo, 2008; Bello et al, 2009), could yield better results. Since cut marks produced with different types of flint cannot be differentiated following a microphotogrametric and geometric morphometric two-dimensional approach, we can conclude that these experiments with

flint can be extrapolated to other archaeological sites with flint artefacts regardless of their source.

3. Experimentation with cut marks produced with different types of quartzite reveal that the quartzite from Olduvai Gorge can be clearly differentiated from the diverse set of Spanish quartzites. This is probably due to the different sized crystals that make up these quartzites, with Olduvai Gorge quartzite presenting 0.5 cm sized crystals, whilst Spanish quartzite crystals range from 177 to 250 μm . Some authors even classify this quartzite as quartz due to these different properties (Perlès, 1991; Sahnouni et al, 1997; Diez-Martín et al, 2010; Sánchez et al, 2012). However, in a strict geological definition, these materials are clearly quartzites, and not quartz (Hay, 1976; Santonja et al., 2014), regardless of its quartz-like behaviour. As observed with flint cut marks, Spanish quartzite cut marks cannot be differentiated among them.

Although significant differences cannot be found at the intra-sample level amongst the different types of flint and amongst the different types of quartzite (except for Olduvai Gorge quartzite), it is safe to say these experiments can be extrapolated to the study of archaeological sites containing flint and quartzite tools, since cut marks produced with these two different raw materials can be characterized.

The study of cut marks holds potential information for our understanding of human behaviour in past human societies. Experiments to identify butchering behaviours should be particularly emphasized. The method presented here allows to create an even tighter link between cut marks and the specific tools contained within the same archaeological assemblage. In the present study, cut marks have been produced using simple flakes, but there is a new generation of experiments in progress, which are being carried out to characterize cut marks produced by different lithic tools, distinguishing between simple or retouched flakes, scrapers, denticulates, cleavers or handaxes. In addition to these variables, others should also be experimentally tested in the future. Among those would be cut mark variability according to different types of carcasses depending on animal size, animal age (regarding hardness or fragility of cortical bone surfaces), the butcher's physical characteristics (different degree of strength applied to cutmarking), and/or the degree of wear-use of lithics. Some of these variables have been recently tested by Braun et al. (2017), who showed that hardness of tool edges and hardness of bones affects cut-mark morphology. Here, we have documented different mark properties according to raw material used. Future research should test these conclusions and see how other variables interact with raw material type to create a range of cut mark morphologies. In addition, as other authors have done with other techniques (Montani et al., 2012; Güth, 2012; Bello et al., 2013), the technique presented here could also be applied to bone tools, prehistoric art or even engraved pottery.

Acknowledgements

We would like to thank TIDOP Group from the Department of Cartographic and Land Engineering of the High Polytechnics School of Avila, University of Salamanca, for the permission to use their tools and facilities. We would also want to acknowledge the Geodynamics Department from Complutense University of Madrid for carefully preparing the thin sections studied throughout this study. Finally we want to recognize the technical support provided by C.A.I. Arqueometry and Archaeological Analysis from Complutense University which has been very useful to carry out the present work. We would also like to thank the anonymous comments of the reviewers.

References

- Adams, D. C., Otarola-Castillo, E., 2013. Geomorph: an R package for the collection and analysis of geometric morphometric shape data. *Methods in Ecology and Evolution* 4, 393-399.
- Bello, SM, Soligo, C., 2008. A new method for the quantitative analysis of cutmark micromorphology. *Journal of Archaeological Science* 35, 1542–1552.
- Bello, SM, Parfitt, SA, Stringer, C. B., 2009. Quantitative micromorphological analyses of cut marks produced by ancient and modern handaxes. *Journal of Archaeological Science* 36, 1869–1880.
- Bello, SM., De Groote, I., Delbarre, G., 2013. Application of 3-dimensional microscopy and micro-CT scanning to the analysis of Magdalenian portable art on bone and antler. *J. Archaeol. Sci.* 40, 2464-2476
- Boschin, F., Crezzini, J., 2012. Morphometrical Analysis on Cut Marks Using a 3D Digital Microscope. *International Journal of Osteoarchaeology* 22, 549–562.
- Braun, DR, Pante, M, Archer, W., 2017. Cut marks on bone surfaces: influences on variation in the form of traces of ancient behaviour. *Interface Focus*. Downloaded from <http://rsfs.royalsocietypublishing.org/> on January 5, 2017
- Choi, K., Driwantoro, D., 2007. Shell tool use by early members of *Homo erectus* in Sangiran, central Java, Indonesia: cut mark evidence. *Journal of Archaeological Science*, 34, 48-58.
- Core R. Team, 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: <https://www.R-project.org/>.
- Dewbury, A.G., Russell, N., 2007. Relative frequency of butchering cutmarks produced by obsidian and flint: an experimental approach. *Journal of Archaeological Sciences* 34, 354–357.
- De Juana, S., Galán, A. B, Domínguez-Rodrigo, M., 2010. Taphonomic identification of cut marks made with lithic handaxes, an experimental study. *Journal of Archaeological Science* 37, 1841–1850.

Diez-Martín, F., Sánchez Yustos, P., Domínguez-Rodrigo, M., Mabulla, A.Z.P., Bunn, H.T., Ashley, G.M., Barba, R., Baquedano, E., 2010. New insights into hominin lithic activities at FLK North Bed I, Olduvai Gorge, Tanzania. *Quaternary Research* 74, 376-387.

Domínguez-Rodrigo, M., de Juana, S., Galán, AB, Rodríguez, M., 2009b A new protocol to differentiate trampling marks from butchery cut marks. *Journal of Archaeological Science*, 36, 2643–2654.

Fernández Jalvo Y., Díez, J. C.; Cáceres, I.; Rosell, J., 1999. Human cannibalism in the Early Pleistocene of Europe. (Gran Dolina Sierra de Atapuerca, Burgos Spain). *Journal of Human Evolution* 37. 591-622.

González-Aguilera, D., Guerrero, D., Hernández-López, D., Rodríguez-González, P., Pierrot, M., Fernández-Hernández, J., 2013. PW, Photogrammetry Workbench. <<http://www.isprs.org/catcon/catcon6.aspx>> accessed 30.04.14.

González-Aguilera, D., López-Fernández, L., Rodríguez-González, P., Guerrero-Sevilla, D., Hernández-López, D., Menna, F., Nocerino, E., Toschi, I., Remondino, F., Ballabeni, A., Gaiani, M., 2016a. Development of an all-purpose free photogrammetric tool. Congress: Development of an all-purpose free photogrammetric tool. Date: 12 to 19 of July of the year 2016, Prague, Czech Republic.

González-Aguilera, D., López-Fernández, L., Rodríguez-González, P., Guerrero-Sevilla, D., Hernández-López, D., Menna, F., Nocerino, E., Toschi, I., Remondino, F.,

Ballabeni, A., Gaiani, M., 2016b. InteGRATED PHOtogrammetric Suite, GRAPHOS. Congress: CATCON7-ISPRS. Date: 12 to 19 of July of the year 2016, Prague, Czech Republic.

Greenfield, H. J., 1999. The origins of metallurgy, distinguishing stone from metal cut-marks on bones from archaeological sites. *Journal of Archaeological Science* 26, 797-808.

Greenfield, H. J., 2002. Distinguishing metal (Steel and low) Tin Bronze from Stone (flint and obsidian) Tool cut marks on bone an experimental approach. En Mahieu J. R. (2002) *Experimental archaeology. Replicating past objects, behaviours and processes*. BAR International Series 1035. 35-54

Greenfield, H. J., 2004. The butchered animal bone remains from Ashqelon, Afridar-Area G. *Antiqot* 45, 243-261.

Greenfield, H. J., 2006a. The butchered animal bones from Newe Yam, a submerged pottery Neolithic site off the Carmel Coast. *J. Israel Prehist. Soc.*, 36 173-200.

Greenfield, H. J., 2006b. Slicing cut marks on animal bones, diagnostics for identifying stone tool type and raw material. *Journal of Field Archaeology* 31, 147-163.

Güth, A., 2012. Using 3D scanning in the investigation of Upper Palaeolithic engravings: results of a pilot study. *J. Archaeol. Sci.* 39. 3105-3114.

Hannus, L. A., 1990. "Mammoth hunting in the New World" en Davis, L.B. y Reeves, B.O.K. (eds): *Hunters on the recent past. One World archaeology* 15, 47-67

- Hay, R., 1976. *Geology of the Olduvai Gorge*. University of California Press, Berkeley.
- Hayden, B., (ed) 1979, *Lithic use-wear analysis*. Proceedings of the Conference on Lithic technology, Burnaby, Canada, 16-20 march 1977. *Studies in Archaeology*, Academic Press.
- Keeley, L. H., 1980, *Experimental determination of Stone Tool uses: a microwear analysis*. University of Chicago Press.
- Knauth, L. P., 1994. Petrogenesis of chert. *Reviews in Mineralogy and Geochemistry*, 29(1), 233-258.
- Luhmann, T., Robson, S., Kyle, S., Boehm, J., 2013. *Close-range photogrammetry and 3D imaging*, Walter De Gruyter, Berlin.
- Maté-González, M.A., Yravedra, J., González-Aguilera, D., Palomeque-González, JF, Domínguez-Rodrigo, M., 2015. Micro-photogrammetric characterization of cut marks on bones. *Journal of Archaeological Science* 62, 128-142.
- Maté-González, M.A., Palomeque-González, JF, Yravedra, J., González-Aguilera, D., Domínguez-Rodrigo, M., 2016. Micro-photogrammetric and morphometric differentiation of cut marks on bones using metal knives, quartzite and flint flakes. *Archaeological, Anthropological Sciences*, DOI 10.1007/s12520-016-0401-5.
- Montani, I., Sapin, E., Sylvestre, R., Marquis, R., 2012. Analysis of Roman pottery graffiti by high resolution capture and 3D laser profilometry. *J. Archaeol. Sci.* 39 3349-3353.
- Olsen, S. L., 1988. The identification of stone and metal tool marks on bone artefact BAR 452, 337-360.
- Palomeque González, J., Maté-González, M. A., Yravedra, J., San Juan-Blázquez, M., García-Vargas, E., Martín-Perea, D. M., González-Aguilera, D., Domínguez-Rodrigo, M., 2016. Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones. *Archeometry*, (Submitted).
- Perlès, C., 1991. Économie des matières premières et économie du débitage: deux conceptions opposées? In: *25 Ans d'Études technologiques en Préhistoire XI Rencontres Internationales d'Archéologie et d'Histoire d'Antibes*. Éditions APDCA, Juan-les-Pins, pp. 35-45.
- Rohlf, F. J., 2015. The TPS series of Software. *Hystrix, the journal faunal of Mammalogy*, DOI: <http://dx.doi.org/10.4404/hystrix-26.1-11264>. http://www.italian-journal-of-mammalogy.it/article/viewFile/11264/pdf_11264
<http://life.bio.sunysb.edu/ee/rohlf/software.html>
- Sahnouni, M., Schick, K., Toth, N., 1997. An experimental investigation into the nature of faceted limestone "spheroids" in the early Palaeolithic. *Journal of Archaeological Science* 24, 701-713.
- Sánchez, P., Díez-Martín, F., Domínguez-Rodrigo, M. Tarrío, A., 2012. Discriminación experimental de los rasgos técnicos en la talla bipolar y a mano alzada en lascas a través de los cuarzos de Naibor Soit (Garganta de Olduvai, Tanzania). *Munibe* 63. 5-26.

- Santonja, M., Panera, J., Rubio-Jara, J., Pérez-González, A., Uribebarrea, D., Domínguez-Rodrigo, M., Mabulla, A., Bunn, H.T., Baquedano, E., 2014. Technological strategies and the economy of raw materials in the TK (Thiongo Korongo) lower occupation, Bed II, Olduvai Gorge, Tanzania. *Quaternary International* 322-323, 181-208.
- Semenov, S. A., 1964 *Prehistoric Technology*, London Cory Adams – NacKay
- Sherratt, E., 2014. Quick Guide to Geomorph v. 2.0. <http://www.public.iastate.edu/~dcadams/PDFPubs/Quick%20Guide%20to%20Geomorph%20v2.0.pdf>.
- Shipman, P., Rose, J., 1983. Early hominid hunting, butchering, and carcass-processing behaviors: approaches to the fossil record. *Journal of Anthropol. Archaeol.* 2, 57-98.
- Shipman, P. Rose, J., 1988. Bone tools an experimental approach. In Olsen S. L. The identification of stone and metal tool marks on bone artefacts. BAR 452. Oxford. 303-336.
- Spennerman, D. H. R., 1990. Don't forget the bamboo on recognising and interpreting butchery marks in tropical faunal assemblages some comments asking for caution. Solomon, S., Davidson, I., Watson. D., eds. *Problems Solving Taphonomy Tempus* 2, 80-101.
- Venables, W. N., Ripley, B. D., 2002. *Modern Applied Statistics with S*. Fourth Edition. Springer, New York. ISBN 0-387-95457-0
- Walker, P. L., 1978. Butchering and stone tool function. *American Antiquity*, 710-715.
- West, J., Louys, J., 2007. Differentiating bamboo from stone tool cut marks in the zooarchaeological record, with a discussion on the use of bamboo knives. *Journal of Archaeological Science* 34, 512–518.
- Wickham, H., 2009. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag, New York.
- Yravedra, J., 2006. *Tafonomía aplicada a zooarqueología*. Aula Abierta. UNED. Madrid.
- Yravedra, J., Morín, J., Agustí, J., Sanabria, P., López Recio, M, López-Frailes, G., Illán Illán J., 2009. Metallurgic implications of cut marks in the end Bronze-Iron age of the Iberian Peninsula. *Gallecia* 28. 76-91
- Yravedra, J., Domínguez-Rodrigo, M., Santonja, M., Pérez González, M., Panera, J., Rubio-Jara, S., Baquedano, E., 2010. Cut marks on the Middle Pleistocene elephant carcass of Áridos 2 Madrid, Spain. *Journal of Archaeological Science* 37, 2469-2479.
- Yravedra, J., Maté-González, M. A., Palomeque-González, J.; Aramendi-Picado, J., Estaca-Gómez, V., San Juan-Blázquez, M., Organista, E., González-Aguilera, D., Cobo, L.; Gidna, A., Uribebarreal del Val, D., Arriaza, M. A., Baquedano E., Mabulla, A., Domínguez-Rodrigo, M., 2016. A new approach to raw material use in the exploitation of animal carcasses at BK (Upper Bed II, Olduvai Gorge, Tanzania): a Micro-Photogrammetric and Geometric Morphometric analysis of cut marks. Submitted.