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FLINT AND QUARTZITE: DISTINGUISHING RAW MATERIAL THROUGH BONE CUT MARKS*

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Since the 1980s, 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 five types of flint and five varieties of quartzite was carried out. Microphotogrammetry and geometric–morphometric techniques were applied to analyse these cut marks. The results show that flint cut marks and quartzite cut marks can be characterized at the assemblage level. Different types of flint produced cut marks that were not significantly different from each other. Cut marks made with Olduvai Gorge quartzite were significantly different from those produced with a set comprising several other types of quartzites. Crystal size, which is larger in Olduvai Gorge quartzites (0.5 mm) than Spanish quartzites (177–250 μm), is discussed as being the main reason for 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.

KEYWORDS: RAW MATERIALS, FLINT, QUARTZITE, CUT MARKS, MICRO-MORPHOMETRY, MICRO-PHOTOGRAMMETRY

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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 frequently the case 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 an 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 1980s, 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; Boschin and Crezzini 2012; Maté-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 (Greenfield 1999, 2002, 2006a,b) or Yravedra *et al.* (2009) have shown that mammal defleshing was carried out using metal tools in periods were 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.* 2010).

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 (Maté-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, 2006a,b), the binocular microscope for high-resolution pictures (Domínguez-Rodrigo *et al.* 2009; De Juana *et al.* 2010), three-dimensional (3D) reconstruction of cut marks made by means of 3D microscopy (Boschin and Crezzini 2012), the Alicona InfiniteFocus 3D imaging microscope (Bello and Soligo 2008; Bello *et al.* 2009) or the use of micro-photogrammetric and micro-morphometric analyses (Maté-González *et al.* 2016; Yravedra *et al.* 2017).

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 from one 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 analysing 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 analysing 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. The cut marks produced with flint come from a selection of different flint stones obtained in different areas: 33 from Vallecas (Madrid, Spain; Fig. 1 (a)(i)), 33 from El Pedernoso 1 (Cuenca, Spain; Fig. 1 (a)(ii)), 35 from El Pedernoso 2 (Cuenca, Spain; Fig. 1 (a)(iii)), 27 from Manzanares (Madrid, Spain; Fig. 1 (a)(iv)) and 189 from Olduvai Gorge (Tanzania, Fig. 1 (a)(v)). All flint samples are classified as nodular chert (Knauth 1994), *with grain sizes varying 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; Fig. 1 (b)(i)), 33 from Jarama (Madrid, Spain; Fig. 1 (b)(ii)), 27 from Yunquera de Henares (Guadalajara, Spain; Fig. 1 (b)(iii)), 34 from Río Cares (Asturias, Spain; Fig. 1 (b)(iv)), 25 from Río Cares 2 (Asturias, Spain; Fig. 1 (b)(v)) and 107 from Olduvai Gorge (Tanzania, Fig. 1 (b)(f)). Spanish quartzites presented quartz crystals with sizes ranging from 177 to 250 µm, whereas the Tanzanian quartzite from Naibor Soit (Olduvai Gorge) showed 0.5 cm quartz crystals. The quartz in all the samples ranges in colour from white and grey to black, forming a tight interlocking network.

Methods

The analysed 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 3D 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 (Fig. 2). It was proved that more stable and precise sensors captured better-quality images, producing results that are more significant.

As in previous work, a *Canon EOS 700D* reflex camera was used, with a 60 mm macro lens, which yielded high-resolution and high-quality images (Canon EOS 700D: type, CMOS; sensor size, 22.3 × 14.9 mm^2; pixel size, 4.3 µm; image size, 5184 × 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 the lighting adjusted to keep the bone permanently well illuminated. The photographic sensor had to be configured at the beginning

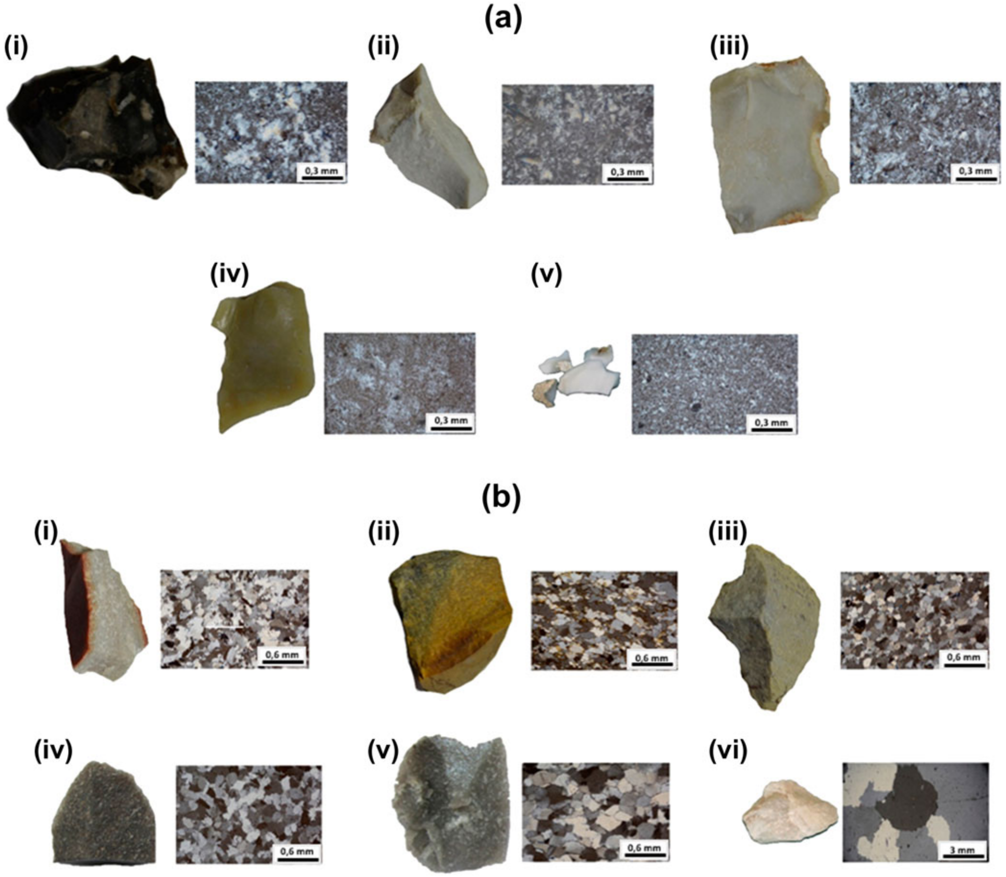


Figure 1 *(a) Thin sections in cross-polarized light and photograph of studied flint samples: (i) Vallecas flint, S1 (Madrid); (ii) El Pedernoso flint, S2 (Cuenca); (iii) El Pedernoso 2 flint, S3 (Cuenca); (iv) Manzanares flint, S4 (Madrid); (v) Olduvai Gorge flint, HS (Tanzania). (b) Thin sections in cross-polarized light and photograph of studied quartzite samples: (i) Segovia quartzite, Q1 (Segovia); (ii) Jarama quartzite, Q2 (Madrid); (iii) Yunquera de Henares quartzite, Q3 (Guadalajara); (iv) Río Cares 1 quartzite, Q4 (Asturias); (v) Río Cares 2 quartzite, Q5 (Asturias); (vi) Naibor Soit – Olduvai Gorge quartzite, HC (Tanzania). [Colour figure can be viewed at wileyonlinelibrary.com]*

of the process to adjust the focus and brightness. A tripod was used to stabilize the camera during the photographic process. Both the moment of exposition of the camera and the lighting remained constant during image data capture. The methodology required placing a millimetric 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 (Fig. 2, image marked with an asterisk '*'). Once the photographs had been taken, they were processed to generate a 3D model for each mark. Consequently, the photographs were treated using the photogrammetric reconstruction software GRAPHOS (inteGRAted PHOtogrammetric Suite, Fig. 2; González-Aguilera *et al.* 2016a,b) 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 (Fig. 3). For data collection, a total of between

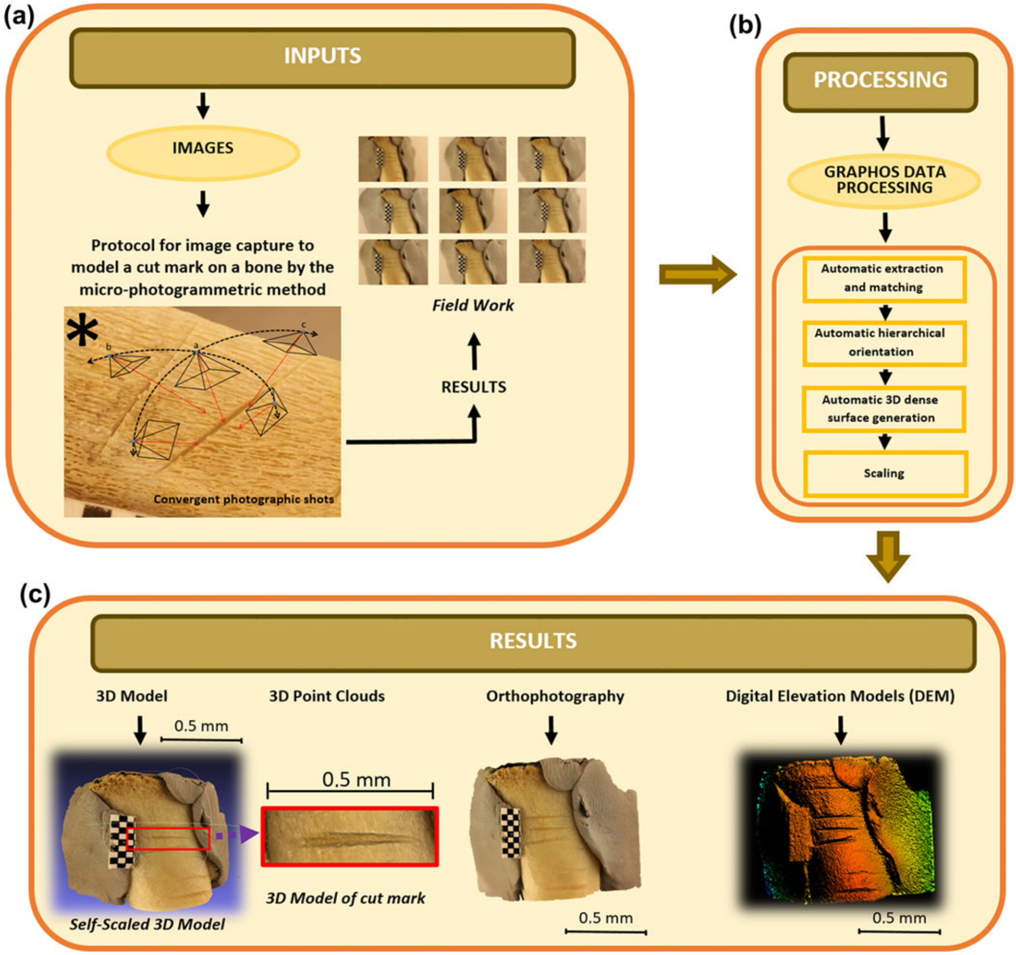


Figure 2 *The workflow of the image-based modelling technique (*, the protocol for image capture to model a cut mark on a bone by the micro photogrammetric method, with convergent photographic shots): (a) master and dependent images in central position; (b) vertical slave images; (c) horizontal slave images. [Colour figure can be viewed at wileyonlinelibrary.com]*

six and nine photographs are taken for each mark. The number of photographs varies depending on the geometry of the bone and the shape of the mark. The 3D reconstruction of each mark takes 30–40 min, depending on the final number of photographs taken.

Our goal with the reconstructions is to maximize both accuracy and completeness. If the separation among images (the baseline) increases, the accuracy will improve, as the intersection of the perspective rays is more favourable, but the completeness of the object will decrease due to the dense cloud algorithms. By contrast, if the separation among images (the baseline) decreases, 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 versus microscopy given that geometric data are dependent from two different sources

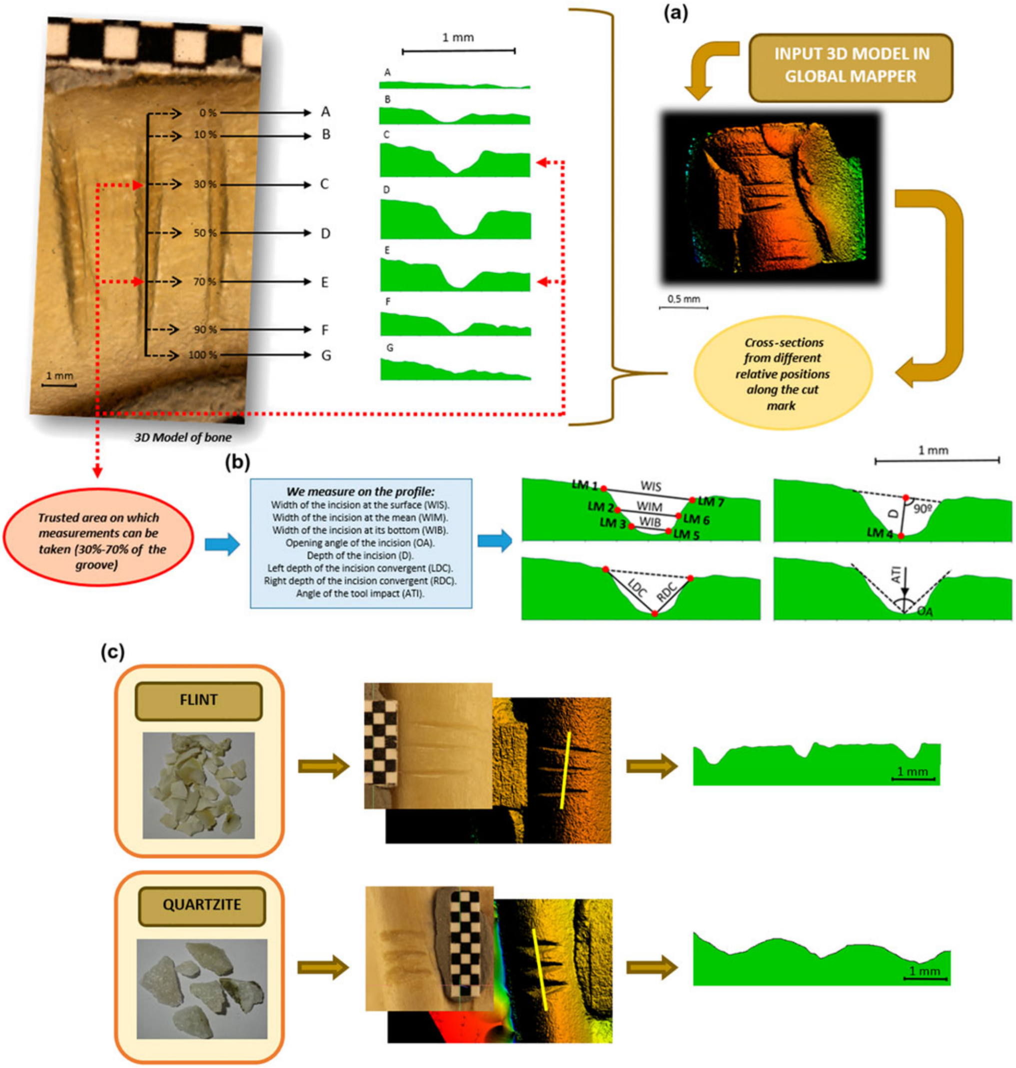


Figure 3 *(a) Representations of cross-sections A–G of the cut mark with regard to its length. (b) The locations of measurements along the profile sensu Bello et al. (2013): the landmarks (LM 1–7) used for the morphometric model are also represented. (c) Cross-sections of the cut marks generated with quartzite and flint flakes, showing detail for the V sections in both types of cut marks. [Colour figure can be viewed at wileyonlinelibrary.com]*

(scaling and photogrammetric reconstruction—PHO), the variance of the PG could be estimated as follows:

$$\sigma_{\mathrm{PG}} = \pm\sqrt{\left(\sigma_{\mathrm{scaling}} \cdot GSD\right)^2 + \left(e_{\mathrm{PHO}} \cdot GSD\right)^2}, \qquad (1)$$

where $\sigma_{\mathrm{scaling}}$ is the scaling precision established as one third of the pixel (Luhmann *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 metres per pixel.

In this way, it is possible to obtain a comprehensive and complete comparison, at the 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 a description, the confidence range for measurement of the marks hardly varies if they are between 30% and 70% of the mark length (Fig. 3 (a)).

A series of measurements including WIS, WIM, WIB, OA, D, LDC and RDC (*sensu* Bello *et al.* 2013) were made on the mark section (Fig. 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.* 2017). 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 component analysis (PCA) tests are carried out using the R freeware (Core R Team 2016). The ANOVA tests consist of a variance analysis of each variable separating the marks by raw material and by 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 that turn out to be statistically more significant in ANOVA tests. The application of ANOVA required the prior use of Bartlett's test in order to confirm that the variance was homogeneous thought the sample. PCA estimates similarities of and differences between marks on a two-dimensional (2D) Euclidean space, and in the present study the raw measurements transformed through scaling were used. The plotting of the PCA results with confidence ellipses was carried out according to Wickham (2009).

A geometric morphometric analysis was performed along with a generalized Procrustes analysis (GPA) as a complement to the multivariate metric analysis (Fig. 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 at 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: LM 2 was located in the middle of the groove; LM 3 was placed approximately at 10% from the end of the mark; LM 4 was at the very end; and LM 5, LM 6 and LM 7 were in opposing positions with regard to LM 3, LM 2 and LM 1 (Fig. 3 (b)) (for a more comprehensive description of these variables, see Maté-González *et al.* 2015). 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 Otarola-Castillo 2013; Sherratt 2014).

Subsequently, a generalized Procrustes analysis (GPA) was applied on the landmark data, followed by a PCA (see LM 1–7 in Fig. 3 (b)). Morphometric disparity analysis was made 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 us to compare objects strictly by their shape. This is achieved by means of an algorithm that, after the 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 regard 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). 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 fulfils the requirements of quick capture, automatic processing of images and accuracy assessment (Maté-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 those made with quartzite (Fig. 3 (a)). These results were similar to the ones observed previously, where flint and quartzite showed differences in shape (Walker 1978; Maté-González *et al.* 2016).

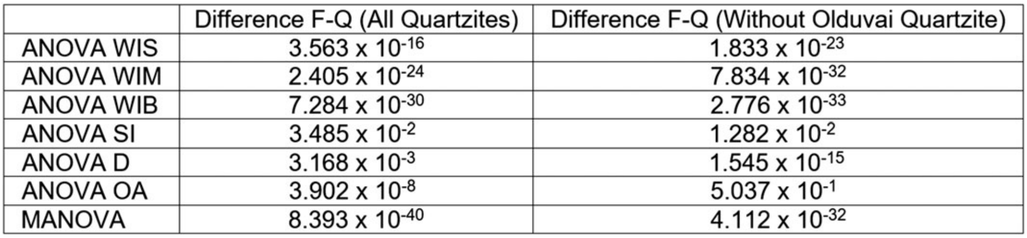
ANOVA and MANOVA tests measuring raw metrics show important differences between flint and quartzite (Table 1). These mostly affect the following variables: WIS, WIB, WIM, SI, D and OA.

A PCA using the most discriminant variables was carried out to compare the cut marks made with both raw material types (Fig. 4 (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 strong overlap in some cases (Fig. 4 (a)). In this experimental sample, when distributing cut marks according to the two types of raw material, the raw measurements showed overall larger dimensions of the variables in cut marks made with quartzite, which enables a correct classification of 69% of marks according to the raw material type (Fig. 4 (c)).

The geometric morphometric 2D analysis of the seven landmarks discards differences caused by dimensional variables and focuses on shape distances (Fig. 4 (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 (Fig. 4 (c)).

Table 1 *The results of the ANOVA and MANOVA tests*

	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}



	Difference F-Q (All Quartzites)	Difference F-Q (Without Olduvai Quartzite)
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ANOVA WIM	2.405×10^{-24}	7.834×10^{-32}
ANOVA WIB	7.284×10^{-30}	2.776×10^{-33}
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MANOVA	8.393×10^{-40}	4.112×10^{-32}

Figure 4 *(a) Principal component analysis (PCA) of cut marks produced with flint (F) and quartzite (Q) tools. (b) GPA test silhouettes of cut marks produced with flint (i) and quartzite flakes (ii). The black points are the centroids associated to each landmark. (c) Linear discriminant analysis (LDA) of (i) measurements and (ii) 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) (see Fig. 3 (b)).*

These results agree with previous comparative experiments of marks made with flint or quartzite (Walker 1978; Maté-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 also shows interesting results. With regard 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 (Fig. 5 (a)) produced with Vallecas, El Pedernoso, Manzanares and Olduvai flint flakes does 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.

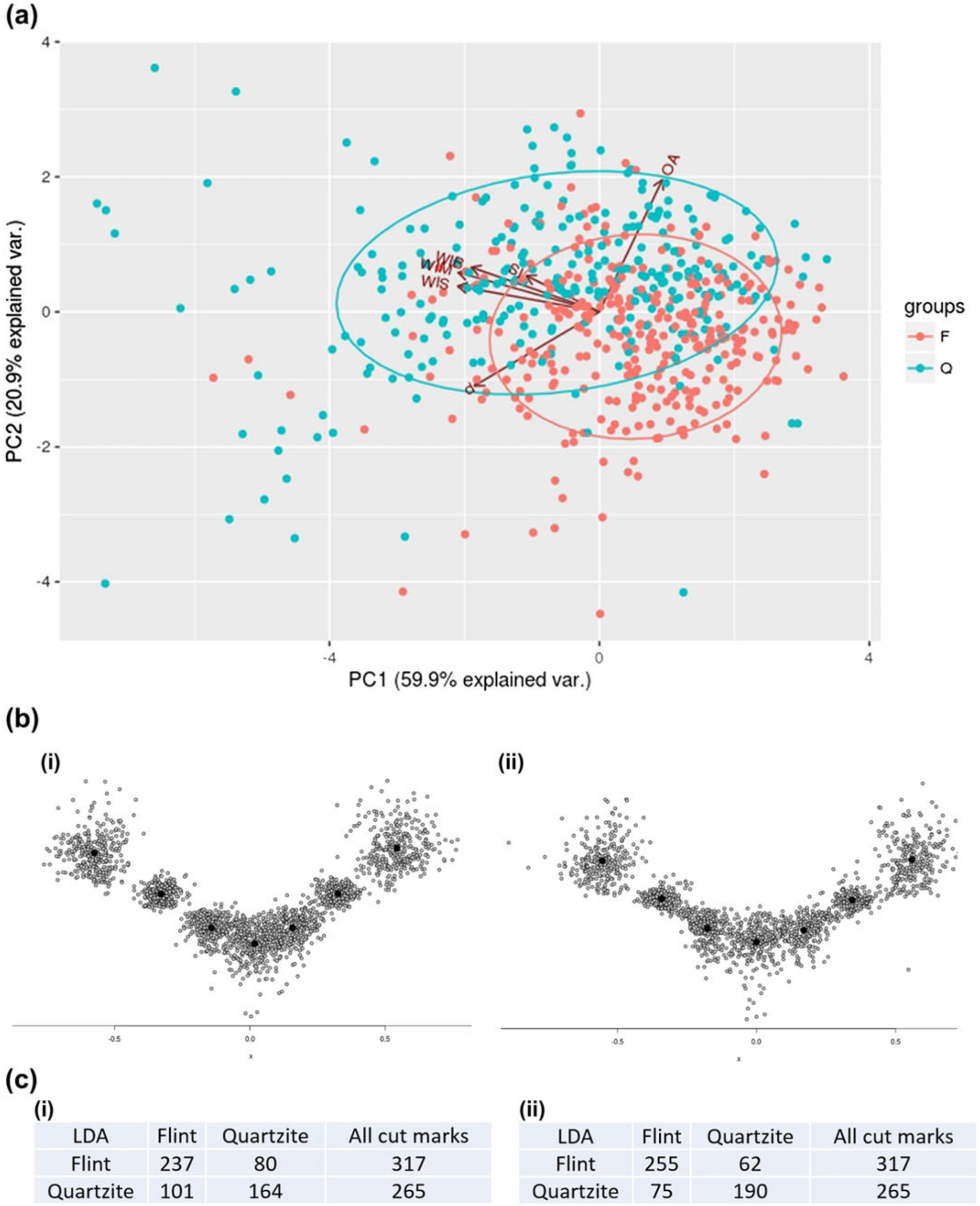
The LDA of measurements includes all cut marks made with flint, including the Olduvai Gorge flint (HS, Fig. 5 (c)). As can be seen, the different flint cut marks cannot be differentiated correctly (Fig. 5 (c)). The LDA shows that in four of the five flint groups, no mark made with flakes gets correctly classified. Cut marks produced by different types of flint flakes are very similar dimensionally and, therefore, difficult to differentiate from one another.

Regarding the GPA, most mark shapes are also very similar, although some morphological variability is recorded (Fig. 5 (b)). A confusion matrix shows that 69% of marks are correctly classified according to flint type (Fig. 5 (c)). 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).

The properties of the quartzite cut marks 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 (Fig. 6 (a)) produced with Segovia (Q1), Jarama (Q2), Yunquera de Henares (Q3), Río Cares 1 (Q4), Río Cares 2 (Q5) and Olduvai Gorge (HC) quartzites displays some clear differences. The Spanish quartzites appear to be 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 one of them indistinguishable from any other in terms of their overall dimensions (Fig. 6 (b)).

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 (Fig. 6 (c)).

When a metric LDA is carried out, excluding the Olduvai Gorge quartzites, it can be observed that the correspondence between quartzites is very homogenous, making it difficult to correctly



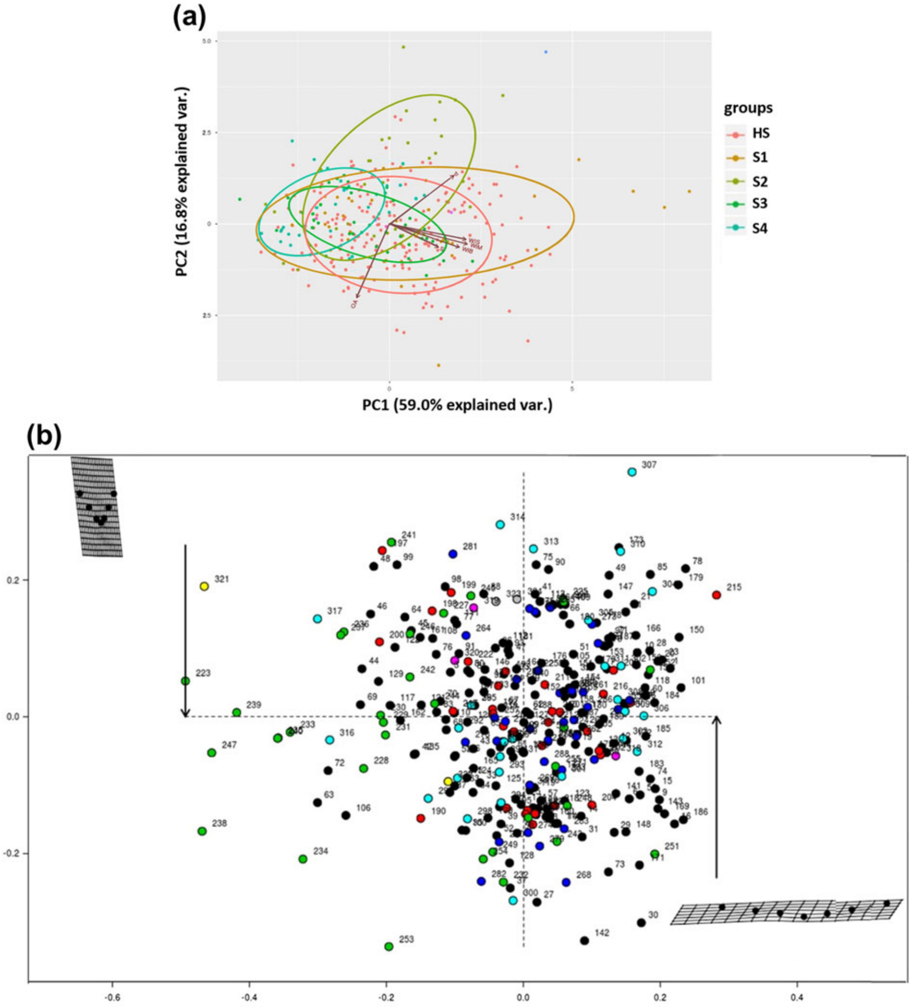
(i)

LDA	Flint	Quartzite	All cut marks
Flint	237	80	317
Quartzite	101	164	265

(ii)

LDA	Flint	Quartzite	All cut marks
Flint	255	62	317
Quartzite	75	190	265

Figure 5 *(a) Principal component 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) Linear discriminant analysis (LDA) of (i) measurements and (ii) 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) (see Fig. 3 (b)). [Colour figure can be viewed at wileyonlinelibrary.com]*



(c) **(i)**

	HS	F1	F2	F3	F4
HS	189	0	0	0	0
F1	33	0	0	0	0
F2	33	0	0	0	0
F3	35	0	0	0	0
F4	27	0	0	0	0

(ii)

	HS	F1	F2	F3	F4
HS	172	8	2	2	5
F1	13	19	0	1	0
F2	16	0	13	1	3
F3	23	3	0	8	1
F4	13	0	4	2	8

Figure 6 *(a) Principal component analysis (PCA) of cut marks produced with different quartzite tools, including Olduvai Gorge quartzites (HC). (b) 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) Linear discriminant analysis (LDA) of morphometric analysis for Segovia (Q1), Jarama (Q2), Yunquera de Henares (Q3), Río Cares 1 (Q4), Río Cares 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) LDA of morphometric analysis for quartzite of Segovia (Q1), Jarama (Q2), Yunquera de Henares (Q3), Río Cares (Q4) and other Río Cares (Q5), cut marks, showing the number of correctly classified marks (diagonal) and those that were incorrectly classified according to flint type (see Fig. 3 (b)). [Colour figure can be viewed at wileyonlinelibrary.com]* classify them. This similarity is such that Q4 is only correctly identified 40% of the time, and Q5 only 45% of the time (Fig. 6 (d)). In contrast, the Q2 cut marks are correctly classified 92% of the time. A confusion matrix shows that only 37% of the marks can be correctly classified according to quartzite type (Fig. 6 (d)).

The results from GPA were analysed by PCA, including all quartzite types (Fig. 6 (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 (Fig. 6 (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 that 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. Due to their petrological and mineralogical characteristics, the Olduvai Gorge quartzites have misled some authors into classifying them as quartz (Sánchez Yustos *et al.* 2012; Santonja *et al.* 2014). This is undoubtedly due to the type of crystallization that these quartzites show, behaving similarly to quartz.

DISCUSSION

The combined dimensional and geometric–morphometric approach to the study of cut marks, comparing marks created by flakes from structurally different raw materials, can yield potentially discriminating results leading to the 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 any specific type of effector. The analysis shown here 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 the 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 sufficiently informative to correctly discriminate three out of every four cut marks, linking them to a raw material type using the same type of effector. At every single stage of this analysis, we have shown that the morphometric properties of marks are more important than the dimensional ones in differentiating 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 become 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 in 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 the 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 Maté-González *et al.* (2015), allows a wide range of samples to be used 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 3D microscopy (Boschin and Crezzini 2012) or an Alicona InfiniteFocus 3D 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 microphotogrammetric and geometric–morphometric 2D 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, while 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 Yustos *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 their quartz-like behaviour. As observed with flint cut marks, it is impossible to linear discriminant analysis between Spanish quartzite cut marks.

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 that 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 emphasized in particular. The method presented here allows us 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 the hardness or fragility of cortical bone surfaces), the butcher's physical characteristics (different degrees of strength applied to cut-marking) and/or the degree of wear-use of lithics. Some of these variables have recently been tested by Braun *et al.* (2017), who showed that the hardness of tool edges and the hardness of bones affect cut-mark morphology. Here, we have documented different mark properties according to the 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.

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