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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 fossil cut marks

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The use of innovative techniques such as micro-photogrammetry and geometric morphometrics may have a major impact on the differentiation of cut marks made with different raw materials and, thus, link butchering processes with stone tool reduction sequences. This work focuses on a sample of cut-marked bones from the Bell's Korongo (BK) site (Upper Bed II, Olduvai Gorge, Tanzania), which is an emblematic early Pleistocene site where a large faunal assemblage, including a diverse megafauna, occurs in association with quartzite and basalt industries. We present a detailed study of a sample of 58 cut marks identified on a set of recently excavated BK fossils, using a micro-photogrammetric and geometric morphometric approach, with the aim of identifying the raw materials used in the butchery of carcasses. In order to carry out this study, we previously carried out an experimental analysis to characterize cut marks and their morphology according to the types of raw material found at BK, namely quartzite and basalt. The results from the experimental study show that there is a good fit between raw material type and cut mark morphology, enabling us to confidently apply this method to the analysis of the cut marks of the BK fossil assemblage. The present study shows that most of the BK cut marks were created by the use of quartzite tools. The efficiency of this type of raw material is emphasized, which explains its curation over the landscape by hominins.

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Olduvai Gorge (northern Tanzania) is one of the main places for the study of the evolution of early human behaviour. Olduvai not only provided the discoveries that led to the definition of the Oldowan lithic industry (Leakey 1931, 1936, 1951), but it has also yielded important hominin discoveries over the past 60 years (Leakey 1959, 1960, 1971; Leakey & Leakey 1964; Leakey *et al.* 1964; Domínguez-Rodrigo *et al.* 2012a, 2013, 2015). Olduvai Gorge also contributed to the foundation of important palaeolandscape research frameworks (Isaac 1981; Potts 1988; Peters & Blumenschine 1995) and fomented the development of taphonomy mainly through the 'hunting-scavenging' debate in the 1980s (Binford 1981, 1988; Bunn 1981, 1982, 1986; Potts & Shipman 1981; Bunn & Kroll 1986; Binford *et al.* 1988). It has also been the testing background of hominin scavenging scenarios (Blumenschine 1986, 1987, 1989; Tappen 1992, 1995; Domínguez-Rodrigo 1994, 1996), as well as other hominin subsistence models (Blumenschine 1988, 1991, 1995; Blumenschine & Selvaggio 1988; Cavallo & Blumenschine 1989; Blumenschine *et al.* 1994; Capaldo & Blumenschine 1994; Selvaggio 1994, 1998; Capaldo 1997, 1998; Domínguez-Rodrigo 1997, 1999, 2001, 2002). Currently, while some researchers still argue that hominin subsistence was based on opportunistic strategies (Blumenschine *et al.* 2007, 2012; Pante *et al.* 2012) several works have provided heuristic information on hominin hunting activities at some Olduvai sites (Monahan 1996; Domínguez-Rodrigo &

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Barba 2006; Bunn 2007; Domínguez-Rodrigo *et al.* 2007, 2009a, 2010a, 2014a; Egeland & Domínguez-Rodrigo 2008; Bunn & Pickering 2010). Some authors propose that early access to meat was an important element of the initial stages of the evolution of human behaviour (Domínguez-Rodrigo *et al.* 2007, 2012a).

While a strong emphasis has been laid on the archaeological record of Bed I, only a few works have deeply analysed the taphonomically rich record of Bed II (Monahan 1996; Egeland 2008; Egeland & Domínguez-Rodrigo 2008). Bell's Korongo (BK) is one of the few Bed II sites where a significant consumption of meat can be taphonomically supported in the lower Pleistocene. A large amount of cut and percussion marks have been identified on the skeletal remains recovered from different archaeological levels at the site (Domínguez-Rodrigo *et al.* 2007, 2009a, 2014b; Egeland & Domínguez-Rodrigo 2008; Organista *et al.* 2015).

The lithic industry of BK is composed of a limited variety of raw materials, amongst which quartzite is the most abundant, followed by basalt, and other very poorly represented raw materials such as chert and gneiss (Leakey 1971; Hay 1976; Kyara 1999; Diez-Martín *et al.* 2009; Domínguez-Rodrigo *et al.* 2014b). It seems likely that each material was used for different activities, but the lack of functional and use-wear studies has hindered the empirical verification of the lithic functionality at most Bed II sites. Due to this lack of analyses, it has traditionally been assumed that there is a functional association between faunal and lithic remains; however, in some sites it has already been observed that such an association can be the result of independent events (Domínguez-Rodrigo *et al.* 2007; Egeland & Domínguez-Rodrigo 2008; Yravedra *et al.* 2016).

Studies involving the analysis of cut marks for the identification of raw materials or tools constitute a rather specialized research field that has been developed since the 1980s, both in experimental (e.g. Walker 1978; Shipman & Rose 1983; Olsen 1988; Spennerman 1990; Greenfield 1999, 2004, 2006a, b; Bello *et al.* 2009; Domínguez-Rodrigo *et al.* 2009b, 2012b; De Juana *et al.* 2010) and archaeological contexts. For instance, Greenfield (1999) was capable of identifying the use of metal tools in the processing of carcasses during the Copper and Bronze Age in Europe. Yravedra *et al.* (2010) were able to observe the use of handaxes in the exploitation of a proboscidean found at Áridos. Bello & Soligo (2008) and Bello *et al.* (2009, 2013, 2015) also identified the use of different types of tools in other archaeological contexts.

In this study, we present a new analytical approach that has not been applied before to an archaeological assemblage, as the combination of micro-photogrammetric, morphometrics and statistics experimental bone assemblages of non archaeological samples (Maté González *et al.* 2015, 2016). These preliminary experimental studies showed how features analysed through this technique could be equally documented on sections along most of the trajectory of the marks and different types of raw material resulted in different mark section morphologies. We are also applying this methodology to study tooth mark morphology generated by different carnivores (work in progress).

BK Bed II Olduvai Gorge

Location and geology

The BK site was found in 1935 at the top of Olduvai Gorge Bed II for L. Leakey. The site is located on the south wall of the Side Gorge, 3 km upstream from its junction with the Main Gorge (Fig. 1). Over the last decade, The Olduvai Paleoanthropology and Paleoecology Project (TOPPP) resumed the excavations at BK in the area adjacent to Leakey's trenches, exposing several discrete archaeological levels and 13 geological levels that together sample a river bar where the edge of the alluvial plain meets the river channel as indicated by the presence of fine-grained sediments (Organista *et al.* 2015).

Stratigraphically, BK is situated directly above Tuff IID, which was recently dated at 1.338±0.024 Ma (Domínguez-Rodrigo *et al.* 2013). The site consists of low-energy fluvial deposits composed of four sedimentary units (Fig. 2). The two lowermost units (Units 1 and 2) contain the archaeological levels: Unit 1 contains levels BK3, BK3b, BK4 and BK5, and Unit 2 contains archaeological levels 1 and 2. These six archaeological levels are mainly composed of clay, silts and sands (from very coarse to very find sand). The archaeological levels also vary in thickness, ranging from 15 cm to 1 m, and present different concentration patterns, with BK1, BK2, BK3, BK4 and BK5 showing clear horizons where the archaeological materials are discretely concentrated (Domínguez-Rodrigo *et al.* 2009a, 2014b; Organista *et al.* 2015).

Fauna

The bone assemblage at BK is composed of a large amount of faunal remains representing a wide array of taxa, of which Bovidae, Equidae and Suidae are the most abundant groups, and ostrich eggshells and megafaunal remains are unusually plentiful (Domínguez-Rodrigo *et al.* 2009a, 2014b; Organista *et al.* 2015).

BK1 and BK2 are dominated by Alcelaphini and Antilophini, but with a higher number of equid remains in BK2. BK3 contains more bones from large fauna (>500 kg), but medium-sized animals (Bunn 1982) are the best-represented animals. BK4 also includes larger animals (*Pelorovis, Syncerus* and *Sivatherium*). BK5 exhibits a wider diversity of taxa ranging from small to large-sized animals including

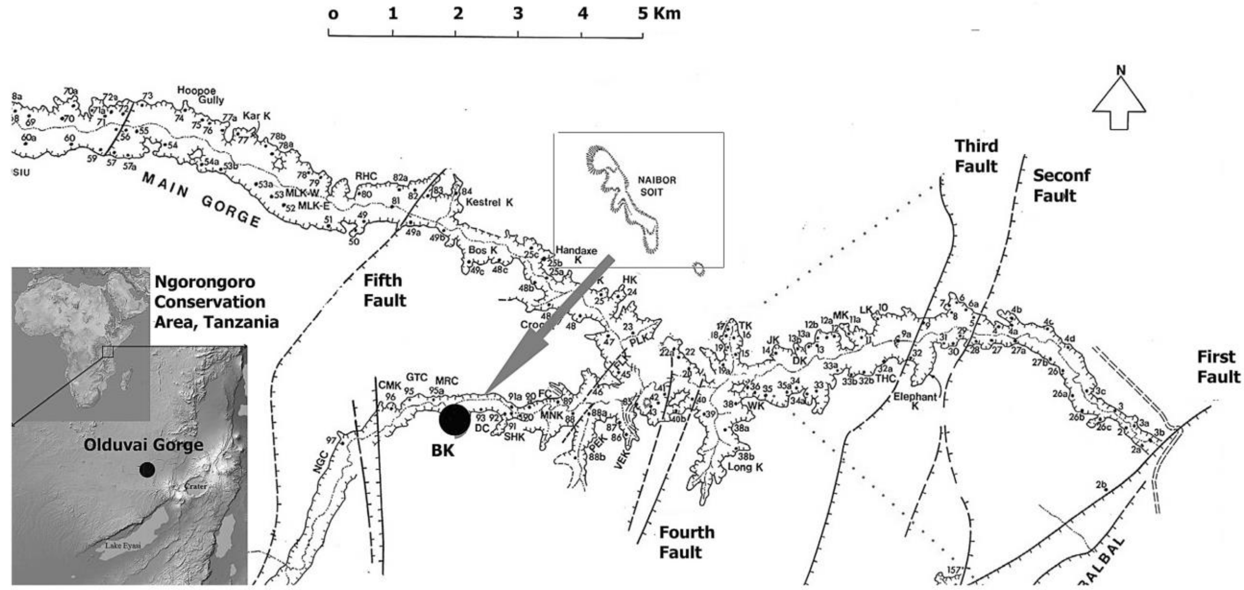

Fig. 1. Location of BK in the Olduvai Gorge and location of the Naibor Soit formation.

hippopotamus and crocodiles, equids, alcelaphines, and *Theropithecus* (Domínguez-Rodrigo *et al.* 2009a, 2014b; Organista *et al.* 2015).

All anatomical areas are represented; however, the least dense parts of the skeleton seem to be underrepresented through the entire sequence. Taphonomic studies (Domínguez-Rodrigo *et al.* 2009a, 2014b; Organista *et al.* 2015) suggest that the assemblage at BK is the result of several depositional events widely separated in time, including natural deaths (probably large game) and hunted and transported animals (small- to medium-sized animals) that were primarily processed by hominins. Orientation analyses indicate that postdepositional processes do not seem to have been prominent, although might explain some minor disturbances. A significant number of specimens show a poor cortical preservation due to postdepositional events; however, there is taphonomic evidence suggesting a primary hominin intervention. One of the most striking features of the BK bone assemblages is the high frequency of cut marks. A total of 161 cut-marked specimens has been found at BK. Cut marks abound on meaty limb elements (humerus, femur, tibia) in all BK levels, highlighting filleting activities on most carcasses. Cut marks have also been found on both the ventral and dorsal sides of rib fragments, reflecting evisceration of carcasses by hominins and further supporting the interpretation of primary access to fleshed carcasses. Along with the numerous cut marks, an abundance of green fractures and percussion marks, and low frequencies of tooth-marked bones in all BK levels support this interpretation and identify carnivores as secondary agents (Domínguez-Rodrigo *et al.* 2009a, 2014b; Organista *et al.* 2015).

Lithics

According to Leakey (1971), a very rich assemblage of stone tools amounting to over 6800 lithic pieces, including 652 whole flakes, 721 tools and almost 400 pieces of utilized material, was recovered. Later excavations conducted by TOPPP confirmed the lithic richness of BK, with a total of 1575 well-preserved lithic pieces, without any sign of abrasion or postdepositional damage (Diez-Martín *et al.* 2009).

The predominant raw material type documented in the four levels is quartzite (>90% in all BK levels). Other raw materials such as hyaline quartz (around 2% per level), basalt (2.44%), nephelinite (1%) and the marginal appearance of chert and gneiss contribute in much lower percentages to the overall count.

Diez-Martín *et al.* (2009) distinguished six different main artefact categories according to the reduction model – freehand and bipolar knapping – and their functionality: (i) manuports/hammerstones, (ii) cores/fragments, (iii) detached objects, (iv) bipolar cores, (v) bipolar flakes/positives and (vi) shatters. These reduction strategies produced different results, freehand flakes being significantly more useful as cutting tools than bipolar products, which show great morphological variability. Only 5% of the freehand detached objects had been retouched. The percentage of retouched tools is even lower amongst the bipolar flakes, with only four examples.

Sample and methods

For the purpose of this study, a total of 58 cut marks from different BK archaeological levels (which

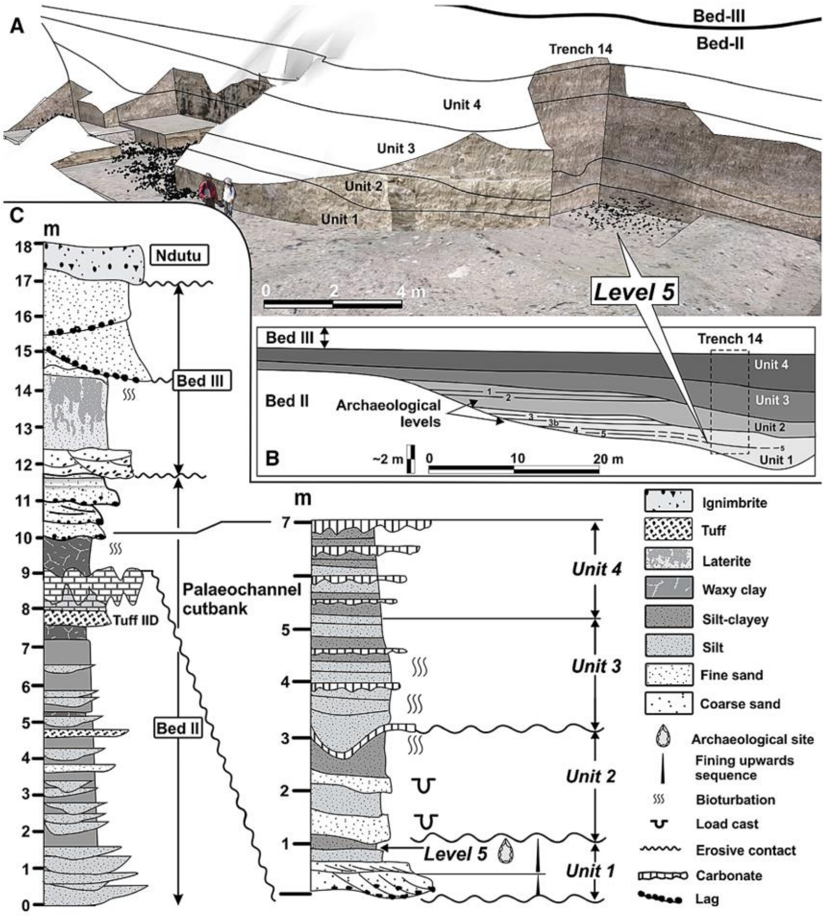

Fig. 2. A. Location of level 5 at BK. B. Detailed stratigraphical section of the four units with the different archaeological levels identified. C. Stratigraphical section across the Bed II–Bed III and Ndutu units (locality 94) in the Side Gorge. [Colour figure can be viewed at wileyonlinelibrary.com]

represents approximately one third of the total number of cut marks identified at the site) was selected (see Fig. S1). BK5b has 13 Number of specimens (NISP) with cut marks (Organista *et al.* 2015), BK4b has 38 NISP with cut marks (Domínguez-Rodrigo *et al.* 2014b) and BK4, BK3, BK2 and BK1 have respectively three, 31, 52 and 24 NISP with cut marks (Domínguez-Rodrigo *et al.* 2009a). The cut marks analysed here and the 3D models are available in Fig. S1 and Table S1.

Cut marks were selected on the basis of their preservation and general condition. We excluded those cut marks that presented poor cortical preservation or some type of alteration, such as the appearance of flaking or the overlay of tooth marks, biochemical alterations, etc. Neither superficial nor inconspicuous cut marks that provided a bad resolution were selected for the study.

High-resolution images obtained through micro-photogrammetry and computer visualization techniques were used 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. 3). It was demonstrated that more stable and precise sensors captured better quality images, producing more significant results. A Canon EOS 700D reflex camera (Table 1) with 60 mm macro lense was used. 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 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. 3). Once the photographs had been taken, they were processed so as to generate a 3D model for each mark. Consequently, the photographs

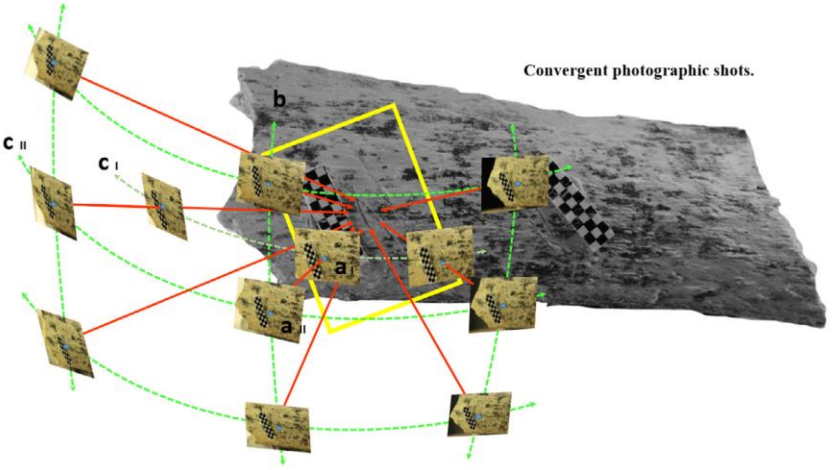

Fig. 3. Protocol for image capture to model cut marks on a bone by the micro-photogrammetric method, with convergent photographic shots. A. Master and dependent images in central position. B. Secondary images of vertical marks. C. Horizontal marks secondary images. [Colour figure can be viewed at wileyonlinelibrary.com]

were treated with the photogrammetric reconstruction software *GRAPHOS* (inteGRAted PHOtogrammetric Suite; Fig. 4) (González-Aguilera *et al.* 2016a, b) or another 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 (Figs 3, 4). For data collection a total of nine to 13 photos was taken for each mark. The number of photos varied depending on the geometry of the bone and the shape of the mark. The 3D reconstruction of each mark took 30–40 min depending on the final number of photos acquired.

Our goal with the reconstructions was to maximize both accuracy and completeness. If the separation amongst images (baseline) increases, the accuracy will improve as the intersection of the perspective rays is geometrically more favourable, but the completeness of the object decreases because of the fault of similarity between adjacent images. By contrast, if the separation amongst 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 photogrammetric and geoinformatics (PG) methods vs. microscopy given that geometric data are dependent on two different sources (scaling and photogrammetric reconstruction, PHO), the precision of the PG can be estimated as follows:

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

where $\sigma_{scaling}$ is the scaling precision established as 1/3 of the pixel (Luhmann *et al.* 2013), e_{PHO} is the reprojection 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 both geometric and statistical levels.

Table 1. Technical specifications of the photographic sensor with macro-lens.

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

Cut marks were measured at mid-length (about 50% of the mark length) as suggested in Maté González *et al.* (2015). According to this work, for a confident comparison of cut marks, the values for the sections between 30 and 70% of the mark length would be the most representative ones (Fig. 5). A series of measurements including width of the incision at the surface (WIS), width of the incision at the mean (WIM), width of the incision at its bottom (WIB), opening angle (OA) of the incision, depth of the incision (D), left depth of the incision convergent (LDC), right depth of the incision convergent (RDC) (*sensu* Bello *et al.* 2013) was taken on the mark section and used as quantitative variables (see Fig. 6 for the location of measurements).

The measurements for each mark section were later compared with experimental samples (see below and Table S1) using a specific program created in R (www.r-project.org) for the analysis of cut marks. The analysis, combining statistical and morphometric methods, facilitates fast analysis of a large number of variables and samples. We analysed metric data using a multivariate principal components analysis (PCA) using R.

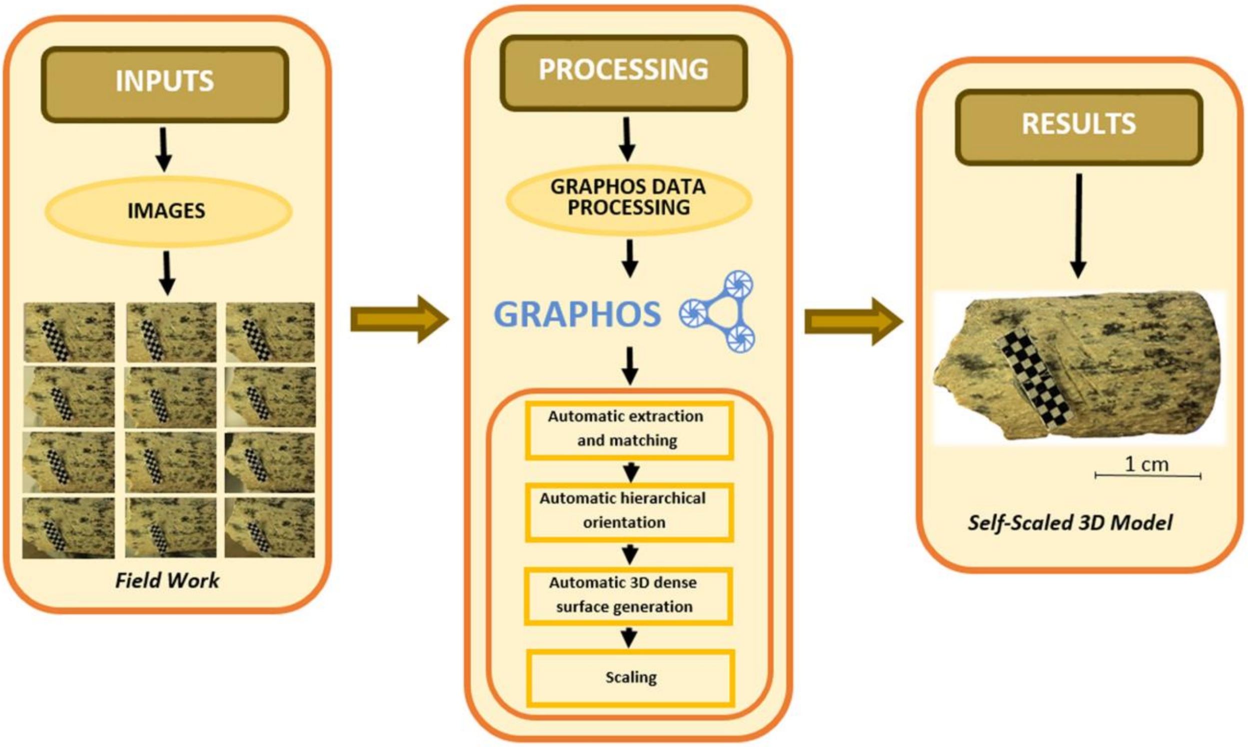

Fig. 4. Workflow of the image-based modelling technique. [Colour figure can be viewed at wileyonlinelibrary.com]

PCA can be used to estimate the similarities and differences of marks on a bidimensional Euclidean space and in the present study it used the raw measurements transformed through scaling. Plotting (using biplots) of the PCA results with confidence ellipses was conducted with the ggplot2 R library.

A geometric morphometric analysis was subsequently performed, as well as a generalized Procrustes analysis (GPA) as a supplementary alternative to the multivariate metric analysis (Fig. 6). In this case, seven identical semi-landmarks per section – as shown in Fig. 6 (LM1–7) – were considered from each mark.

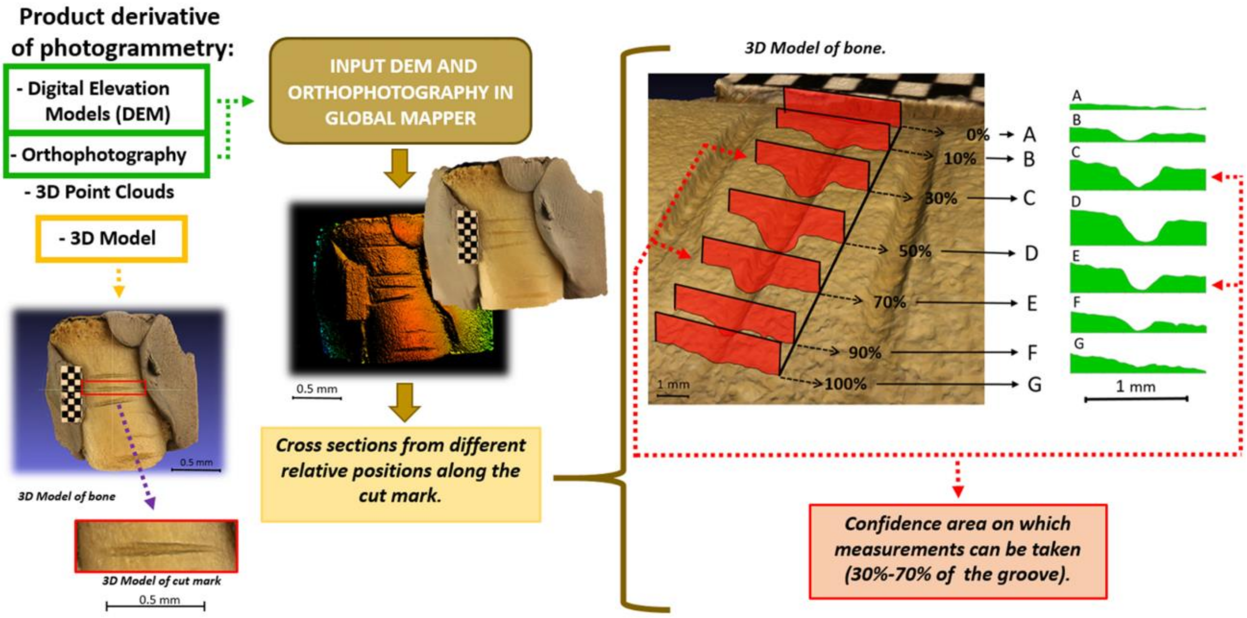

Fig. 5. Representation of the A–G sections of the cut mark regarding its length. [Colour figure can be viewed at wileyonlinelibrary.com]

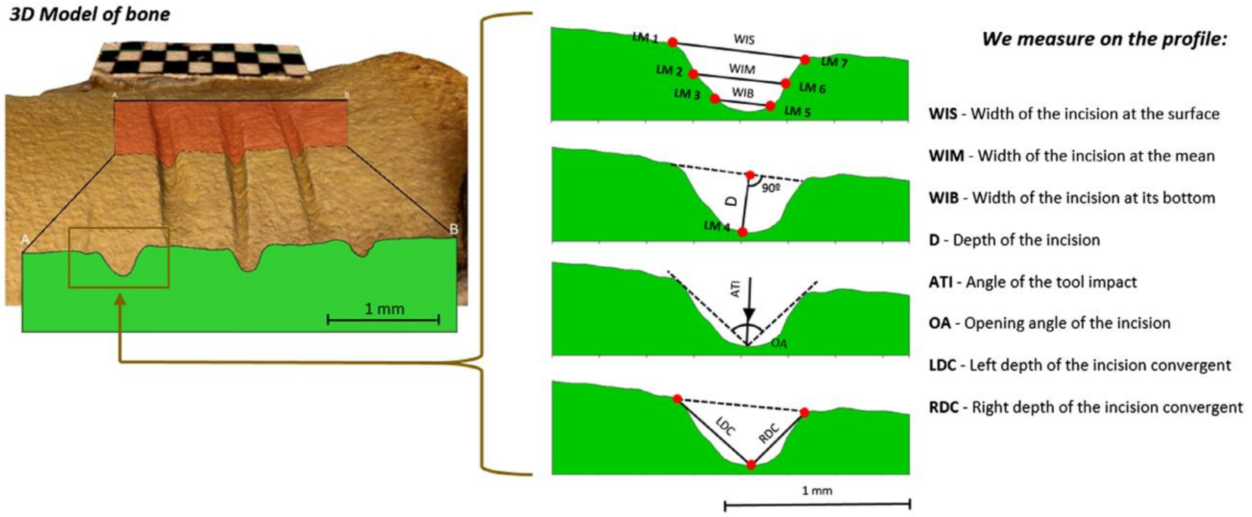

Fig. 6. Location of measurements *sensu* Bello *et al.* (2013). Semi-landmarks (LM1–7) used for the morphometric model are also represented. [Colour figure can be viewed at wileyonlinelibrary.com]

Semi-landmarks were digitalized using tpsUtil (v. 1.60.) and tpsDig2 (v. 2.1.7), as explained in Maté González *et al.* (2015). The locations of the landmarks responded to the measures considered for the statistical analysis, as seen in Fig. 6. These semi-landmarks are the same as proposed in previous research (Maté González *et al.* 2015, 2016). Semi-landmark 1 (LM1) was found at the beginning of the left line in the mark section; LM2 appeared in the middle of this line; LM3 was placed approximately at 10% of the right end of the mark; LM4 was at the very end; and LM5, LM6 and LM7 in opposite positions to LM3, LM2 and LM1, respectively (Fig. 4). The resulting tps file was imported into R and analysed using the 'geomorph' library (Sherratt 2014). Lastly, a discriminate lineal analysis (DLA) was performed to estimate the differences amongst the several groups of marks defined by raw materials. The DLA function included in the MASS R package was used. We conducted a geometric morphometric bidimensional analysis of the seven semi-landmarks (see LM1–7 in Fig. 6), which were first subjected to a GPA. This technique normalizes the form information by the application of superimposition procedures. This involves the translation, rotation and scaling of shapes defined by landmark configurations.

As our goal was to compare the cut marks identified at BK and determine which raw materials were used, we performed several experiments with the same types of raw materials as found at Olduvai Gorge such as quartzite and basalt (Fig. 7). A total of 198 cut marks produced with chert tools, 107 cut marks generated with quartzite flakes from the Naibor Soit (Olduvai Gorge) and 85 cut marks produced with basalt collected in nearby Olduvai was compared (Fig. 7). Quartzite and basalt are the two main raw materials found in the Bed II sites (Hay 1976; Kyara 1999). Basalt outcrops can also be found in the river channels that flow from the slopes of the Olmoti and Lemagrut volcanoes, 9 km to the east (Kyara 1999). The quartzite found at BK comes from the Naibor Soit, an inselberg located close to the site (Hay 1976; see Fig. 1).

Considering that the main raw materials identified at BK are quartzite and basalt, in this paper we compare the samples of BK with the experiments carried out with quartzite and basalt flakes. These experiments show a comparative analysis of cut marks made with quartzite, basalt and flint flakes. The results suggest a substantial difference in groove section morphology between flint and quartzite and between quartzite and basalt. By contrast, small differences are observed between basalt and flint. The absence of flint at BK means that a comparative analysis of cut marks at the site is only possible for basalt and quartzite. Figure 8 shows the differences between cut marks produced with quartzite vs. those made with basalt, and the differences between quartzite and flint, as well as the similarities of flint and basalt.

Results

The models developed through the micro-photogrammetric method are based on oblique photography acquired with 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 photogrammetric error (mm) = ±0.0058; average precision (mm) = ±0.0168). It should be noted that the camera was self-calibrated to simultaneously compute the interior and exterior camera parameters. In particular, a complete calibration, which includes 12 interior parameters (focal length (1),

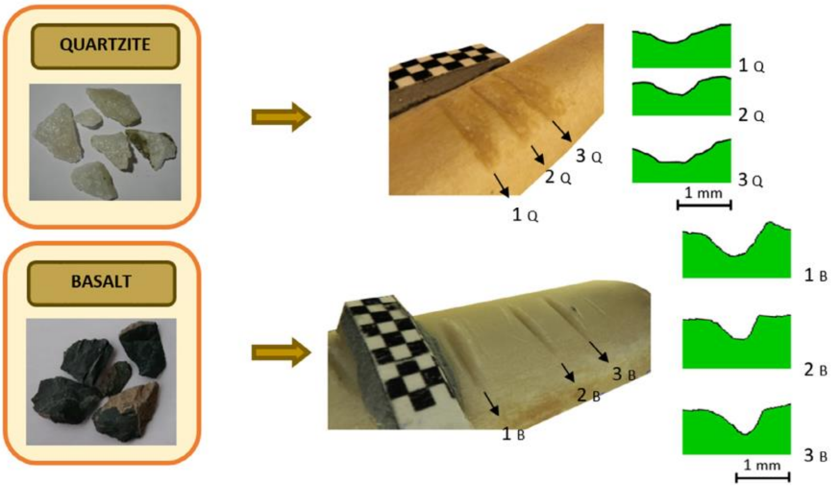

Fig. 7. Cut marks generated with a quartzite and with a basalt flake. Detail of the V sections in the three types of marks. [Colour figure can be viewed at wileyonlinelibrary.com]

principal point (2) and distortion centre (2), radial (3) and tangential (2) distortion, scaling and affinity factors (2)), was applied (Fraser 1980). This self-calibration is suitable and valid when reflex cameras are used and some theoretical parameters are known.

The sections of the 58 BK cut marks (Fig. S1) are highly variable. Cut marks are located on different anatomical elements and different bone sections including shafts and axial and cranial elements. A close observation of the marks confirms that they vary in width and depth, equally showing open _/-sections and closed V-sections. Each mark has its own peculiarities and only a statistical analysis that considers several variables will establish a reliable relationship between cut marks and raw materials (Fig. 7). Despite the variability of mark sections produced with the same type of raw material, we can generally say that quartzite cut marks are wider, shallower and show a _/-shaped section, whereas marks produced with basalt are deeper and somewhat narrower, showing more of a V section. These observations are more nuanced than some of the traditional definitions of cut marks as straight grooves showing the typical morphology with a V section (e.g. Binford 1981; Bunn 1981; Potts & Shipman 1981; Shipman & Rose 1983; Fisher 1995; Giacobini & Patou Mathis 2002). This is especially so given that section form depends on the raw material used (Maté González *et al.* 2016), and also on other variables such as the degree of use wear of tool edge, carcass body size, age at death, physical conditions and the methodology used by the butcher. These other variables should also be studied in future experimental analyses, as well as other forms of bone surface modifications, such as tooth marks.

A PCA using raw metrics was performed to compare the cut marks from BK with cut marks created with basalt and quartzite flakes in experimental frameworks (Fig 9). The 95% confidence ellipses of the PCA of the measurements specified in Fig. 6 do not clearly relate the cut marks found at BK with any of the selected raw

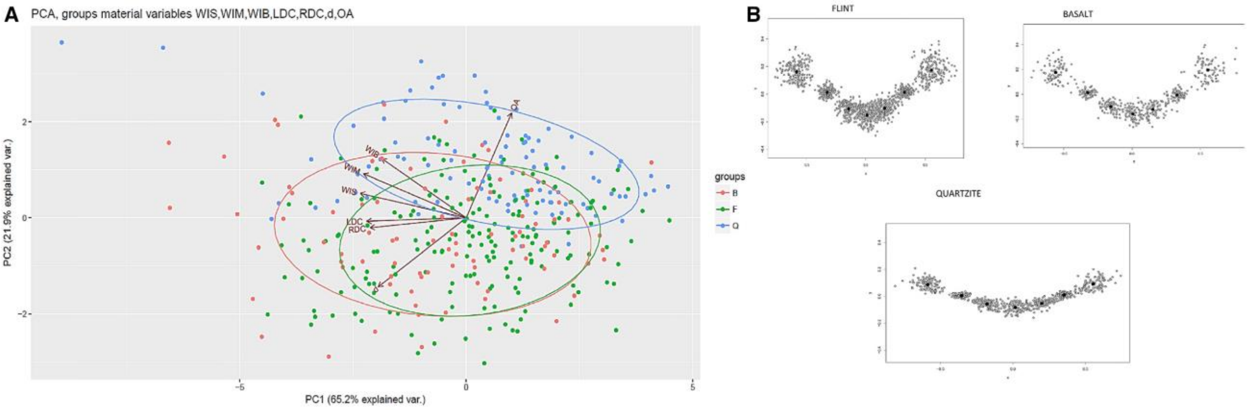

Fig. 8. A. Principal components analysis (PCA) and B. GPA with each LM centroid of cut marks produced by basalt, quartzite and flint. [Colour figure can be viewed at wileyonlinelibrary.com]

materials given the wide range of sizes documented (Fig. 9). It is possible to observe a trend towards the results obtained in experiments with quartzite flakes, but the degree of resolution is insufficient and thus the test is inconclusive. The divergence of the archaeological and the experimental samples is partly due to the intentional selection of the clearest cut marks at BK, which were better documented on the bigger marks identified; hence the bigger size difference reported in Fig. 9.

Because this biometric test was not conclusive, we conducted a geometric morphometric bidimensional analysis of the seven landmarks. Figure 10 displays in grey the LMs of each specimen, and in black the common centroid (Fig. 10). According to this test the morphology of the BK cut marks is closer to the experimental marks produced with quartzite than to those created using basalt flakes.

Then, another PCA was conducted (Fig. 11). In the PCA plot, the morphological variability is summarized in a 'deformation grid'. This test highlights larger differences between the cut marks produced with basalt and the other two groups. Marks made with basalt are deeper and narrower than those of BK and those with quartzite, whereas the group of marks found at BK and the quartzite marks overlap considerably.

Finally, to clearly test the correlation between BK cut marks and those experimentally performed with quartzite, a DLA was conducted. This test indicates the separation between the two groups. Of the 58 BK cut marks, 47 (81%) appear to be classified within the group of marks made with quartzite and 11 (19%) with basalt. The rest of the marks are grouped as marks produced with basalt. These results do not mean that this smaller percentage of the BK cut marks were actually produced with basalt, but that those marks cannot be pooled with the quartzite group due to their inherent variability. In fact, this small percentage of marks still falls in the variability range corresponding to cut marks produced with quartzite.

Considering the results obtained from our morphometric analysis we conclude that most BK cut marks were performed with quartzite tools, which also matches the information obtained from lithic studies, as quartzite is the predominant raw material at BK (Diez-Martín *et al.* 2009).

Discussion

The present analysis enables us to establish a direct relationship between the faunal remains and the lithic industry discovered at BK. We observed a positive correlation between the cut-marked fauna and one type of raw material. Previously, lithic studies from BK and other Bed II sites have shown that quartzite is the predominant raw material (Leakey 1971; Hay 1976; Kyara 1999; Diez-Martín *et al.* 2009). According to morphometric criteria, we can interpret that 81% of the cut marks identified at BK were made with quartzite tools. Thus, we suggest that activities related to the exploitation of carcasses (e.g. filleting or disarticulation) were conducted using this type of material.

This new methodological approach provides high-resolution functional information about the use of stone tools and can ultimately make up for the lack of other analyses such as use-wear studies.

It should be highlighted that regardless of the methodology, either through photogrammetric reconstruction (Maté González *et al.* 2015, 2016) or other similar 3D procedures (e.g. Bartelink *et al.* 2001; Kaiser & Katterwe 2001; Bello & Soligo 2008; Bello *et al.* 2009, 2013, 2015; Boschin & Crezzini 2012), 3D analyses contribute to providing a more comprehensive approach to the identification and characterization of

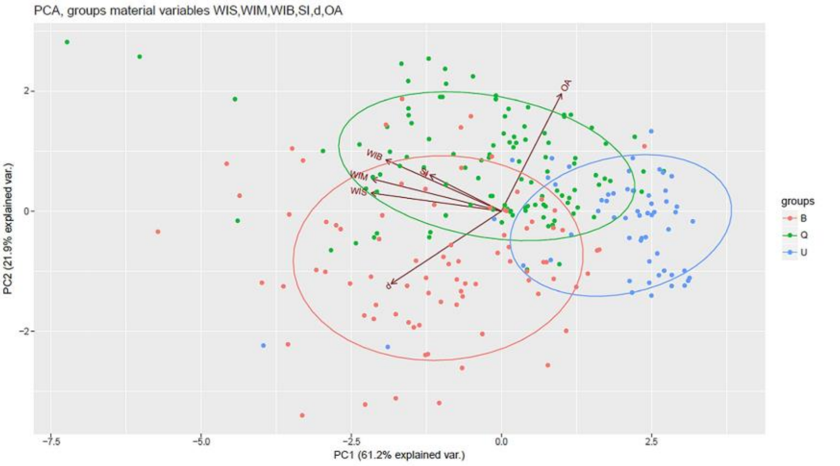

Fig. 9. Principal components analysis (PCA) of cut marks produced with quartzite (Q), basalt (B) and BK (u) tools. [Colour figure can be viewed at wileyonlinelibrary.com]

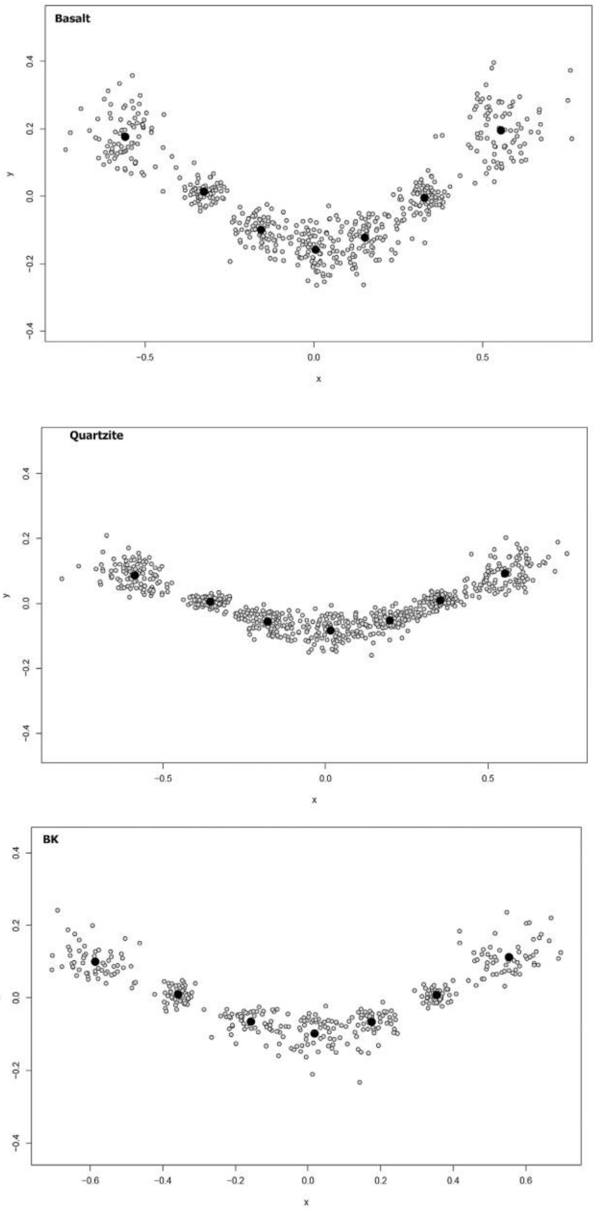

Fig. 10. Generalized Procrustes analysis (GPA) test. Silhouettes of cut marks of BK and marks produced with basalt and quartzite. Black points are the centroids associated with each semi-landmark.

marks. Considering the analytical possibilities offered by 3D analyses and the results obtained here, as well as in previous analyses (Maté González *et al.* 2016), morphometric studies of cut marks appear to be more effective than strictly metric analyses of the same marks, because the former introduces an objective way of classifying marks that is not dependent on the analyst's expertise. Maté González *et al.* (2016) observed that cut marks produced by chert, quartzite and metal could be better distinguished when applying morphometric criteria instead of metric measurements. Metric analyses could only clearly distinguish marks produced with metal from those made with quartzite, whereas differences between metal and chert, as well as between quartzite and chert, were not so obvious. On the contrary, a morphometric approach allowed for a clear differentiation of the three groups of marks when comparing chert, quartzite and basalt (Fig. 8); although there was a close resemblance between the cut marks produced with chert and basalt when performing a biometric study, larger differences could be inferred from a morphometric perspective (Fig. 8).

In view of these results, the methodology presented here could be used in future research to investigate controversial topics such as the differentiation of cut marks from similar marks created by other natural processes, such as trampling. Although there are many works on cut marks and trampling (e.g. Andrews & Cook 1985; Behrensmeyer *et al.* 1986; Olsen & Shipman 1988; Fiorillo 1989; Giacobini & Patou Mathis 2002; Domínguez-Rodrigo *et al.* 2009b), there is still an ongoing debate on the interpretation of certain marks with important implications for the understanding of human behaviour. For instance, a 3D analysis of the Dikika marks (McPherron *et al.* 2010, 2011; Thompson *et al.* 2015; discussed by Domínguez-Rodrigo *et al.* 2010b, 2011; Domínguez-Rodrigo *et al.* 2012b) followed by a 2D GMM analysis might shed some light on the debate on the first evidence of meat consumption.

It may also be interesting to analyse the relationship between cut marks and the lithic tools according to the mark morphology in order to corroborate whether different activities (e.g. filleting, disarticulation, defleshing) leave different marks or not. Such analysis would contribute to the interpretation of the oldest cut marks (Domínguez-Rodrigo *et al.* 2005) and in so doing the analysis might provide further information to the debate on hunting vs. scavenging during the early stages of human evolution.

The method used here is an alternative to other more expensive and more time-consuming methods such as SEM or confocal laser microscope analyses (Maté González *et al.* 2015). A study testing the accuracy of this method and others in the identification of traces of cut marks is in progress and results should show which (if any) of the methods provides a more accurate representation of cut mark sections and their properties.

Recent experimental work on cut marks using confocal microscopy is very promising (e.g. Pante *et al.* 2017), although the technique still needs developing properly before being useful for interpreting bone surface modifications of fossils. Although the experimental sample used by Pante *et al.* (2017) is not big enough for solid statistical analysis, the main shortcoming in their study is that the final mark shapes that they analysed are not the original shapes, but instead are shapes derived through the use of polynomial

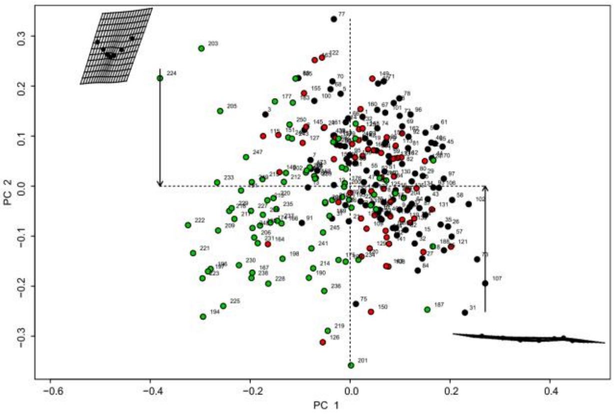

Fig. 11. Principal components analysis (PCA) of the GPA, where quartzite-related marks are in black, basalt in green and BK in red. [Colour figure can be viewed at wileyonlinelibrary.com]

algorithms that 'modify' the original shape as captured by the profilometer due to the presence of discontinuities and gaps. Even if it is assumed that these derived mark sections are as close to the real mark sections as confocal microscopy can get, the resulting sections obtained are highly dependent on the protocol used for scanning each mark. As Pante *et al.* (2017) acknowledge 'the measurements recorded by the three analysts were not identical' because 'differences in the position and orientation of the mark relative to the optical pen resulted in small variations in the data captured'. This additional analytical variable, which introduces some distortion, is further biased when several marks are scanned at the same time, because of differences in levelling and orientation of the marks. Regardless of whether one or several marks are scanned at the same time, the average inter-analyst error was still as high as 15%. We are currently unaware of how these biases may affect mark interpretation.The high accuracy in classification of marks using this method is virtually identical to traditional lower resolution methods (e.g. hand lenses) because the overall morphology of cut and tooth marks is widely divergent (Blumenschine *et al.* 1996). It remains to be seen how useful this method is for the classification of marks created by different agents or effectors whose modifications are morphologically more similar. Further work in this regard is highly encouraged. As it stands, this more expensive and time-consuming method does not seem to show any improvement in mark identification compared to traditional low-resolution methods.

Conclusions

Three main conclusions have resulted from this work. First of all, we have confirmed the feasibility of a technique that had only been applied in experimental assemblages before. As confirmed by our research, the 3D reconstruction of marks provides an appropriate degree of resolution to distinguish cut marks produced with certain raw materials. In addition, we have shown the ease of use and versatility of this technique for a precise analysis of cut marks and the study of larger samples of bones with cut marks in a short time.

Secondly, we have verified the potential of 2D geometric morphometrics as a problem-solving approach for mark interpretation, obtaining better results than the classical approach based on strict metric measurements. Although sometimes the metrics of cut marks may point out some differences related to the raw material used, e.g. metal-quartzite (Maté González *et al.* 2016), in most cases such analyses are inconclusive, whereas geometric morphometrics seem to highlight such differences more accurately, but obviating the allometry introduced by size difference. Thirdly, we have documented the relationship between BK cut marks and the lithic industries found at the site, the great majority of cut marks corresponding to the use of quartzite tools. This is in accordance with previous interpretations provided by lithic analyses.

Hence, we can conclude that the 3D reconstruction of marks and a posterior GMM analysis can serve as a powerful and high-resolution taphonomic tool in order to better understand and interpret archaeological sites. However, we think that further experimental analyses are necessary to properly assess the potential of this technique; either by analysing marks produced with other raw materials, or by reproducing new cut marks combining diverse stone tools such as handaxes, retouched tools, etc. Similarly, experiments including other types of surface modifications (e.g. trampling, tooth marks) could be new areas of application of the techniques described here.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at http://www.boreas.dk.

Fig. S1. Inventory with photographs and sections of cut marks of BK.

Table S1. Statistical data of cut marks from BK, according to both types of raw material: quartzite and basalt.