VNiVERSiDAD D SALAMANCA

TESIS DOCTORAL

Implicaciones de la fotogrametría y de las técnicas láser en la identificación y caracterización de las trazas antrópicas sobre restos óseos en los yacimientos arqueológicos del Pleistoceno.

Miguel Ángel Maté González

Ávila, 2017

Implicaciones de la fotogrametría y de las técnicas láser
en la identificación y caracterización de las trazas antrópicas
sobre restos óseos en los yacimientos arqueológicos del Pleistoceno
(Tesis Doctoral, Universidad de Salamanca, Ávila).

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Dr. Diego González Aguilera

Ilustración de la portada
Cristina Sáez Blázquez

Esta ilustración está basada en las imágenes:

- *Homo habilis* hunting, artwork. C013/9577
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- A group of *Homo habilis* use their sharp tools
  to cut the meat from this rhinoceros carcass in
  Tanzania. Fuente: DK FindOut

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Implicaciones de la fotogrametría y de las técnicas láser en la identificación y caracterización de las trazas antrópicas sobre restos óseos en los yacimientos arqueológicos del Pleistoceno.

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Las ciencias aplicadas no existen,
sólo las aplicaciones de la ciencia.

Louis Pasteur

Implicaciones de la fotogrametría y de las técnicas láser en la identificación y caracterización de las trazas antrópicas sobre restos óseos en los yacimientos arqueológicos del Pleistoceno.

Tesis Doctoral presentada por Miguel Ángel Maté González

<u>Informe de los Directores de Tesis</u>

La Tesis Doctoral "*Implicaciones de la fotogrametría y de las técnicas láser en la identificación y caracterización de las trazas antrópicas sobre restos óseos en los yacimientos arqueológicos del Pleistoceno*", presentada por Miguel Ángel Maté González, se inserta en la línea de investigación y análisis de restos óseos en yacimientos arqueológicos por medio de la utilización de geotecnologías fotogramétricas y de láser escáner.

Se trata de una línea muy original y relevante en la comunidad científica internacional, con una clara propuesta metodológica de bajo coste que ha deparado exitosos resultados en el campo de la tafonomía. Más concretamente, se han investigado y analizado cientos de marcas de corte en hueso tanto en laboratorio como en yacimientos, además y al ver que la técnica empleada ha sido exitosa se ha optado por ampliar sus aplicaciones incorporando el análisis de marcas de diente producidas por carnívoros.

Se trata asimismo de una línea de investigación promovida y desarrollada por el Grupo de Investigación del Dr. José Yravedra Sainz de los Terreros que viene desarrollando propuestas en el seno de proyectos de investigación competitivos en colaboración con otros grupos punteros a nivel nacional e internacional, como el Grupo de Investigación TIDOP (http://tidop.usal.es) de la Universidad de Salamanca, con quienes se ha colaborado durante el desarrollo de esta Tesis Doctoral o con el proyecto TOPPP (http://www.olduvaiproject.org/) entre otros.

La Geomática y en particular las geotecnologías fotogramétricas vienen experimentando una serie de innovaciones de gran alcance que han transformado profundamente su contexto de aplicación frente a las aplicaciones más modernas y costosas (microscopios electrónicos de barrido) que además conllevan la restricción de no poder trabajar con ellas in situ. Estas innovaciones se articulan fundamentalmente en torno a la capacidad de captura sencilla y ágil de imágenes, el procesamiento automático de las mismas, la generación de modelos tridimensionales métricos de gran resolución/precisión y el análisis estadístico y morfométrico de los resultados. Ha sido precisamente este último aspecto estadístico/morfométrico lo que ha aportado una mayor originalidad al campo de la fotogrametría, sin olvidar la propia escala de trabajo y la necesidad de deparar modelos micro-fotogramétricos con resoluciones/precisiones impensables hasta hace unos años.

La Tesis Doctoral aborda un adecuado y amplio estado del arte de manera que permite identificar claramente la oportunidad estratégica de la aportación que se realiza como lo demuestra el hecho de que la Tesis se articula en torno a un buen número de artículos científicos publicados en revistas con impacto reconocido. Siete de ellas pertenecientes al primer cuartil-Q1 y alto factor de impacto (Journal of Archaeological Science, Boreas, Journal of Microscopy, Archaeometry, Palaeogeography, Palaeoclimatology, Palaeoecology y Archaeological and Anthropological Sciences) y una perteneciente a una revista indexada (Journal of Archaeological Science Reports).

Estos artículos han verificado los correspondientes procesos de evaluación crítica y revisión por parte de expertos internacionales de trayectoria reconocida. Estas contribuciones se centran en:

- El desarrollo de una metodología basada en la micro-fotogrametría que permite el análisis estadístico y morfométrico de marcas de corte en hueso.

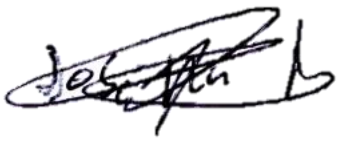
- La realización de un estudio comparativo y la validación de la técnica micro-fotogramétrica con otras técnicas ya existentes y consolidadas como las técnicas microscópicas.

- La realización de un estudio concreto de las marcas de corte en hueso tanto en laboratorio como en yacimientos arqueológicos que permite evidenciar y diferenciar las herramientas y las materias primas con las que se realizaron dichas marcas, provenientes de la acción humana.

- La realización de un estudio concreto de las marcas de diente en hueso tanto en laboratorio como en yacimientos que permite evidenciar y diferenciar los diferentes tipos de animales carnívoros que han intervennido sobre el hueso.

La Tesis Doctoral concluye con el correspondiente apartado de Conclusiones en el que de forma precisa y concreta se especifican las principales aportaciones realizadas de tal manera que puedan ser objeto de crítica y de proyección hacia el desarrollo de futuros trabajos integrados en diferentes líneas de investigación.

En Ávila, a 5 de Mayo de 2017,



Dr. José Yravedra Sainz de los Terreros

Dr. Diego González Aguilera

Listado de artículos publicados

Esta Tesis Doctoral está formada por un compendio de siete artículos científicos publicados en revistas internacionales de impacto JCR y uno en una revista indexada. A continuación se enumeran dichas publicaciones.

- **<u>Micro-photogrammetric characterization of cut marks on bones.</u>**

Maté-González, M. Á.[1], Yravedra, J.[2], González-Aguilera, D.[1], Palomeque-González, J. F.[2] & Domínguez-Rodrigo, M.[2, 3] (2015).

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[2] Department of Prehistory, Complutense University, Prof. Aranguren s/n, 28040 Madrid, Spain.
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Journal of Archaeological Science 62, 128-142.
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- **<u>Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones.</u>**

Palomeque-González, J. F.[1], **Maté-González, M. Á.[2, 3]**, Yravedra, J.[1, 4], San Juan-Blázquez, M.[1], García Vargas, E.[1], Martín-Perea, D. M.[4], Estaca-Gómez, V.[1], González-Aguilera, D.[2] & Domínguez-Rodrigo, M.[1, 4] (2017).

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[4] IDEA (Institute of Evolution in Africa), Museo de los Orígenes, Plaza de San Andrés 2, 28005 Madrid, Spain.

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- **Assessment of statistical agreement of three techniques for the study of cut marks: 3D Digital Microscope, Laser Scanning Confocal Microscopy and Micro-Photogrammetry.**

Maté-González, M. Á.[1, 2], Aramendi, J.[3], Yravedra, J.[3, 4], Blasco, R.[5], Rosell, J.[6, 7], González-Aguilera, D.[1] & Domínguez-Rodrigo, M.[3, 4] (2017).

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Journal of Microscopy 0, 1–15.

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Publicado online: 5 mayo 2017

Publicado: -

- **Micro-photogrammetric and morphometric differentiation of cut marks on bones using metal knives, quartzite and flint flakes.**

Maté-González, M. Á.[1, 2], Palomeque-González, J. F.[3], Yravedra, J.[3, 4], González-Aguilera, D.[2] & Domínguez-Rodrigo, M.[3, 4] (2016).

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Archaeological and Anthropological Sciences

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- **<u>Flint and quartzite: Distinguishing raw material through bone cut marks.</u>**

Maté-González, M. Á.[1, 2], Yravedra, J.[3, 4], Martín-Perea, D. M.[5], Palomeque-González, J. F.[3], San Juan-Blázquez, M.[3], Estaca-Gómez, V.[3], Uribelarrea, D.[5], Álvarez-Alonso, D.[6], Cuartero, F.[7], González-Aguilera, D.[1] & Domínguez-Rodrigo, M.[3, 4] (2017).

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Archaeometry

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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 cut marks.**

Yravedra, J.[1, 2], **Maté-González, M. Á.[3, 4]**, Palomeque-González, J. F.[1], Aramendi, J.[1, 2], Estaca-Gómez, V.[1], San Juan Blazquez, M.[1], García Vargas, E.[1], Organista, E.[1, 2], González-Aguilera, D.[3], Arriaza, M. C.[2], Cobo-Sánchez, L.[1, 2], Gidna, A.[5], Uribelarrea del Val, U.[6], Baquedano, E.[2, 7], Mabulla, A[8]. & Domínguez-Rodrigo, M.[1, 2] (2017).

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Boreas.
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- **FLK West (Lower Bed II, Olduvai-Gorge, Tanzania): A new early Acheulean site with evidence for human exploitation of fauna.**

Yravedra, J.[1, 2], Diez-Martin, F.[3], Egeland, C. P.[4], **Maté-González, M. Á.[5, 6]**, Palomeque-González, J. F.[1], Arriaza, M. C.[2], Aramendi, J.[1, 2], García Vargas, E.[1], Estaca-Gómez, V.[1], Sanchez, P.[3], Fraile, C.[3], Duque, J.[3], de Francisco Rodriguez, S.[3], González-Aguilera, D.[6], Uribelarrea, D.[7], Mabulla, A.[8], Baquedano, E.[2, 9] & Dominguez-Rodrigo, M.[1, 2] (2017).

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Boreas.

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- **On Applications of Micro-photogrammetry and Geometric Morphometrics to Studies of Tooth Mark Morphology: the modern Olduvai Carnivore Site (Tanzania).**

Arriaza, M. C.[1, 2], Yravedra, J.[2, 3], Domínguez-Rodrigo, M.[2, 3, 4], **Maté-González, M. Á.[5, 6]**, García Vargas, E.[3], Palomeque-González, J. F.[3], Aramendi, J.[2, 3], González-Aguilera, D.[6] & Baquedano, E. [2, 7] (2017).

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Resumen:

La tafonomía durante las últimas décadas ha demostrado ser una disciplina de gran relevancia para la explicación e interpretación de los yacimientos arqueológicos y paleontológicos. La tafonomía es una disciplina que permite proponer diferentes tipos de soluciones a los diversos problemas interpretativos encontrados en los yacimientos arqueológicos. A través de la experimentación y de su enfoque analógico deductivo permite proponer hipótesis explicativas.

Durante los últimos años el análisis de las marcas de corte ha generado una gran expectación. Este tipo de trazas están asociadas a la acción humana y pueden resultar de gran importancia para explicar el comportamiento de las poblaciones prehistóricas. De este modo, las marcas de corte resultan ser una herramienta clave en la explicación del debate caza-carroñeo, y pueden ayudar a explicar qué pasos se siguen en el procesado de una carcasa animal. Es relevante también el análisis de las marcas de corte en relación a la selección de las materias primas con las que fueron realizadas dichas marcas, en cuanto al aprovechamiento de las carcasas. Por lo tanto, es crucial, la definición correcta y la información obtenida de estas y también la realización de una identificación de los materiales utilizados en el proceso de aprovechamiento de los animales.

Desde finales del siglo XIX, los investigadores toman conciencia de la relevancia que puede tener el estudio de las alteraciones que aparecen sobre los huesos, catalogándolas en un primer momento de forma descriptiva. A raíz de la irrupción de la tafonomía en la investigación arqueológica, algunos investigadores han tratado de discriminar las distintas clases de marcas que aparecen en los huesos, experimentando con diferentes métodos para observar mejor las marcas de corte. En la actualidad, la metodología más utilizada, se basa en la aplicación de técnicas microscópicas usando para estas investigaciones microscopios electrónicos de barrido (*Scanning Electron Microscope* - SEM).

En estos últimos años, los investigadores, a partir de estas técnicas, han sido capaces de lograr resultados espectaculares gracias a las mediciones tridimensionales que han podido obtener de las marcas de corte en huesos. La documentación 3D de las marcas de corte con estas técnicas microscópicas obtiene muy buenos resultados, pero también plantea diferentes inconvenientes: utiliza equipos económicamente muy

costosos, en muchos casos las muestras necesitan de una preparación antes de realizar el proceso, sólo técnicos especialistas en el campo pueden realizar un manejo óptimo del instrumento y por último su principal inconveniente, es que es un equipo fijo de trabajo, por lo que no se puede desplazar hasta el yacimiento arqueológico.

Con el fin de resolver todas estas problemáticas y con el objetivo de mejorar la metodología ampliando el volumen de los datos susceptibles de ser analizados, en esta Tesis Doctoral se explica el uso de la fotogrametría y de la visión computacional para llevar a cabo estos estudios. Más concretamente, se describe el proceso de captura de datos, el procesado de los mismos y los análisis estadísticos y morfométricos realizados a los datos resultantes obtenidos a partir de estas técnicas. Para realizar este estudio, se han llevado a cabo varios cientos de siluetas de marcas de cortes experimentales en huesos y en fósiles, realizados con diferentes materias primas (sílex, basalto, cuarcita y metal). Esta muestra constituye una de las mayores bases de datos de este tipo recopiladas hasta el día de hoy. Por último, se sugieren nuevas líneas de investigación a las que este procedimiento podría ser fácilmente aplicable.

Abstract:

Taphonomy has proved to be a very important discipline in explaining and interpreting archaeological and paleontological sites over the last few decades. Taphonomy is considered a discipline which allows us to propose different types of solutions to various interpretative problems found in archaeological sites. Through experimentation and its analogical deductive approach we can suggest explicative hypotheses that aid in the interpretation of these sites.

During the last couple of years, the analysis of cut marks has created great expectations. These kinds of marks are associated with human activity and can present extreme value when explaining behavioural attributes of prehistorical populations. As a result of this, cut marks turn out to be a key tool for the development of debates, such as the hunter-scavenger debate, and can also aid in the interpretation of the steps that follow during butchering activities in relation to animal carcasses. Another remarkable application of this field can be found in the analysis of cut marks; regarding the raw material selection in the tools used to produce these cut marks during the exploitation of an animal carcass. It can be seen as crucial how a correct definition of the information obtained from these studies can aid in the development and identification of raw materials used in the process of animal exploitation.

Since the end of the XIX century, researchers have become aware of the importance of studying the changes which appear on bone surfaces, firstly cataloguing these artefacts through descriptive means. Due to the introduction of taphonomy in archaeological investigation, some researchers have tried to distinguish the various different types of marks which usually appear on the surface of bones, trying out different methodological approaches to analyse and observe these marks under a higher resolution. Currently, the most used methodological approach is based on the application of microscopic technology and the use of Scanning Electron Microscopes (SEM) to scan the alterations observable on bone surfaces.

Over the last few years researchers have been able to achieve great results thanks to the three-dimensional measurements which they have been able to obtain from cut marks on bones. While 3D documentation of cut marks through these microscopic techniques have been successful, they do not come without their disadvantages; the higher costs of the equipment used, the essential and necessary preparation of the

samples before studies can be carried out, as well as the need to rely only on technicians specialised within this field in order to accomplish an optimal use of the instruments. Finally the equipment cannot be moved to the archaeological site as they require a fixed and stable environment, generating additional problems for field workers.

With the purpose of resolving all these problems, improving this methodological approach, increasing the amount of reliable data that can be analysed as well as the use of photogrammetry and digital reconstructions, this doctoral dissertation provides an explanation and solution to the problems described above. More specifically; the collecting of data, the processing of said data as well as the statistical and morphometrical analysis carried out on the obtained data will be deeply described within this thesis. In order to achieve this task, several hundreds of experimental cut mark cross-sections produced by different raw materials (flint, basalt, quartzite and metal) have been processed, as well as an additional study of fossils. This sample presents one of the biggest databases compiled of this type of data so far. Lastly, new lines of investigation are suggested in which this methodological approach can easily be applied.

Índice:

Introducción 1

Hipótesis del trabajo 15

Objetivos 17

Estructura de la Tesis Doctoral 19

Sección I: Metodológica 25

Artículo 1: 29

Artículo 2: 49

Artículo 3: 63

Sección II: Aplicación experimental al estudio de las marcas de corte sobre restos óseos 83

Artículo 4: 87

Artículo 5: 103

Sección III: Aplicación sobre restos fósiles en yacimientos arqueológicos 131

Sección III. I. Aplicación sobre el estudio de las marcas de corte 135

Artículo 6: 137

Artículo 7: 155

Sección III. II. Aplicación sobre el estudio de otros procesos tafonómicos 175

Artículo 8: 177

Sección IV: Conclusiones 191

IV. I. Conclusiones sobre la metodología desarrollada para el estudio de marcas de corte 193

IV. II. Conclusiones sobre el estudio de las marcas de corte 195

IV. III. Conclusiones sobre los estudios realizados en marcas de diente 197

Sección V: Perspectivas futuras 199

V. I. Metodología 201

V. II. Marcas de corte. 202

IV. IV. Marcas de diente 205

Referencias bibliográficas 207

Anexo I: Datos estadísticos de las revistas 225

Anexo II: Otras publicaciones 241

Congresos internacionales 243

Anexo III: Repercusión de los artículos entre la comunidad científica 251

1. Introducción

La investigación en el campo de la arqueología ha evolucionado mucho en los últimos años. Esto se debe principalmente a la multidisciplinariedad de los equipos de trabajo. Junto a la incorporación de diferentes especialistas dentro de los equipos de investigación (con presencia de geólogos, topógrafos, matemáticos, físicos, químicos, biólogos, informáticos, etc.), también han sido muy importantes los diferentes avances tecnológicos, el desarrollo de software y hardware en el ámbito informático, el avance de la microscopía, la creación de nuevos algoritmos matemáticos y la mejora de los ya existentes, la evolución de la estadística, así como el uso de otras técnicas o metodologías usadas en diferentes disciplinas de la ciencia.

La aplicación y puesta en práctica de las disciplinas y ciencias anteriormente citadas, que pueden interrelacionarse de forma transversal y que son capaces de interactuar entre sí de forma interdisciplinar, han permitido avanzar en los campos de la investigación, de la divulgación y del tratamiento del patrimonio arqueológico. Gracias a ello, se han podido crear nuevas metodologías de investigación, mejorar las ya existentes o adaptar diferentes técnicas o métodos de otras disciplinas a las necesidades que exige una investigación concreta en un campo específico de la arqueología. En consecuencia, se posibilita una investigación arqueológica más precisa, capaz de efectuar estudios y análisis con mayor exactitud y de realizar una amplia divulgación de los resultados acorde con las necesidades del investigador, de una manera más gráfica y visual, para abrir estas investigaciones a un público no experto.

En esta Tesis Doctoral se ha desarrollado una nueva metodología de investigación, basada en la reconstrucción tridimensional, en el estudio y en la divulgación de resultados, a partir de análisis estadísticos y morfométricos en el campo de la tafonomía.

La tafonomía es una disciplina que tuvo su origen en la geología, siendo Efremov (1940) el primero en denominar esta ciencia. A groso modo, dicha ciencia se encarga de analizar todos los procesos que suceden desde que un ser vivo muere, hasta que llega a la mesa de laboratorio del especialista. De este modo y resumiendo, según esta definición, la tafonomía sería la ciencia que se encarga del estudio de los procesos que rodean a los restos orgánicos de humanos y animales en su proceso de fosilización, lo que se ha llamado, el paso de la biosfera a la litosfera de dichos individuos. En consecuencia, también implica una investigación sobre las causas de la muerte de un ser vivo, los procesos post mortem en la fase de pre-enterramiento, incluyendo los fenómenos cadavéricos y todos aquellos que intervienen durante la sedimentación. Podría decirse que a partir de la muerte de un ser vivo, comienza una nueva vida, que es la vida tafonómica, que sólo termina con la destrucción final del fósil. En esta vida tafonómica tendrían lugar todos estos procesos a los que hemos hecho referencia: muerte del ser con sus posibles causas, fase de pre-enterramiento, fase de sedimentación y a continuación seguiría la fase post-sedimentaria, que incluye todos los procesos de recuperación de los restos, análisis y mecanismos de restauración si los hubiera.

Aunque nos hemos referido a la tafonomía como disciplina que estudia los restos óseos, hay que considerar también los restos de cualquier ser vivo con independencia de que sean animales o vegetales. Del mismo modo, como la tafonomía estudia los procesos de enterramiento y el contexto donde los restos se encuentran, también puede estudiar los restos inorgánicos de un yacimiento como consecuencia de su pertenencia al contexto en el que se integran los restos fósiles. Por lo tanto, la tafonomía estudia los restos fósiles, su contexto y todos los materiales asociados.

La aplicación de la tafonomía a la arqueología ha tenido un desarrollo peculiar. En general y en la actualidad podemos decir que la tafonomía está cada vez más integrada dentro de los equipos multidisciplinares. Pero antes de llegar a esta fase, ha tenido que pasar por un desarrollo complicado.

Desde el S. XIX diferentes autores interpretaron algunos fenómenos arqueológicos aplicando análisis experimentales de trasfondo tafonómico para poder ofrecer explicaciones demostrables (Lartet, 1860; Peale, 1870; Lartet y Chisty, 1875; Martin, 1909). La tafonomía como ciencia se basa en el uniformitarismo, y como tal, toda explicación que propone se basa en el actualismo y debe ser empíricamente demostrable. Es decir, las explicaciones que se ofrecen tienen que ser contrastables. Por ello desde finales del S. XIX y comienzos del S. XX, algunos autores trataron de ofrecer explicaciones sobre los procesos de conservación y fosilización de los yacimientos (Martin, 1907-1910). Pasada la mitad del S. XX se empezó a dar un mayor impulso a la tafonomía, especialmente en lo que se refiere al estudio de la arqueología Paleolítica, con el fin de evaluar las estrategias económicas de los primeros homínidos (White, 1952-1955). Pero el verdadero punto de inflexión de la tafonomía y su aplicación a la arqueología no llegará hasta el año 1981. En dicho año, toda una generación de investigadores publicará importantes trabajos sobre el tema (Haynes, 1980; Binford, 1981; Brain, 1981; Gifford, 1981; Shipman, 1981; Bunn, 1982).

De todos ellos, y por no desviarnos del hilo central de esta investigación, sólo nos vamos a referir al célebre trabajo de Bob Brain con su libro "*The hunters or the hunted*" en el que se prueba con argumentos tafonómicos, que los australopitecos no eran cazadores sino que más bien, fueron presas de otros depredadores, ya fueran leopardos, hienas o aves. En dicha obra, se muestra también, como los primeros yacimientos con acumulaciones de homínidos asociados a fauna, no eran fruto de la acción humana, sino que más bien eran el resultado de las acumulaciones generadas por diversos tipos de carnívoros.

Otro trabajo emblemático es "*Bones: Ancient Men and Modern Myths*", de Lewis R. Binford, que supuso una revolución y ha sido el motor que ha dado un gran impulso a la tafonomía moderna. En este libro, se discute el papel de los primeros *Homo* en la formación de los yacimientos arqueológicos y se analiza su capacidad cinegética, proponiendo a los primeros *Homo* como carroñeros marginales. Desde entonces y hasta ahora, la tafonomía ha sido objeto de una gran evolución, superando las interpretaciones de Binford y proponiendo otros modelos interpretativos, que dan mayor protagonismo al ser humano y que demuestran sus capacidades cinegéticas en fechas muy antiguas (Domínguez-Rodrigo et al., 2007).

La tafonomía durante estos últimos años ha desarrollado diversas líneas de investigación con resultados sorprendentes. Por ejemplo, mediante análisis tafonómicos se puede discriminar si una acumulación fósil de fauna ha sido realizada por un carnívoro o si se debe a otro tipo de actuación. En lo que se refiere al ser humano, se puede precisar con un grado de resolución óptimo si un homínido accedió a una carcasa animal antes de que lo hiciera un carnívoro y en este caso, precisar qué clase de carnívoro era.

Siguiendo una de estas líneas de trabajo, una de las lagunas que ha quedado en la investigación tafonómica, es constatar con qué tipo de herramientas procesaban los homínidos las carcasas que trataban. Algunos autores han realizado análisis para diferenciar las marcas que se producen cuando un individuo procesa una presa, y si estas fueron realizadas con un tipo de herramienta u otra. Así Greenfield (1999, 2004) trata de ver si los animales sometidos a dichos procesos en diferentes etapas de la prehistoria europea, eran tratados con herramientas de metal y/o sílex. Como complemento de esta investigación, otros autores han efectuado trabajos experimentales para discriminar cómo cambian las marcas de corte en función de la herramienta o la materia prima empleada. En consecuencia, dichos autores han experimentado con diferentes materias primas como el sílex, la obsidiana, el metal, la cuarcita, etc. (Olsen 1988; Greenfield, 1999, 2004, 2006a, b; Bello y Soligo, 2008; Yravedra et al., 2009), concha (Choi, 2007), industria ósea (Hanus, 1990; Shipman y Rose, 1988), bambú (Spennerman, 1990; West y Louys, 2007), o diferentes clases de útiles líticos (Walker, 1978; Shipman y Rose, 1983; Bello et al., 2009; Domínguez-Rodrigo et al., 2009; De Juana et al., 2010; Galán y Domínguez-Rodrigo, 2013). Sin embargo, como veremos más adelante estos trabajos presentan algunos problemas y limitaciones.

En esta línea de evolución de la ciencia tafonómica nace esta Tesis Doctoral. En tafonomía, el estudio de las marcas de corte es bastante más relevante de lo que pudiera parecer. Las marcas de corte sobre huesos son la principal evidencia directa que demuestra el acceso que tuvieron los seres humanos a los recursos cárnicos. Dichas marcas, se producen cuando se desliza un útil cortante sobre la superficie de un hueso para extraer la carne. Las evidencias de huesos con marcas de corte más antiguas que se conocen, provienen de los yacimientos de Gona y Bouri que datan de 2.5-2.6 m.a. (De Heinzelin et al., 1999; Semaw et al., 2003; Domínguez-Rodrigo et al., 2005). En los yacimientos anteriormente citados, nos es imposible saber si los seres humanos cazaron las presas, pero es innegable, que las marcas de corte que aparecen en ellas indican que estos primeros humanos tuvieron acceso a recursos cárnicos en fechas muy antiguas. Del mismo modo, la presencia de marcas de corte en huesos humanos ha permitido constatar posibles canibalismos en diferentes tipos de homínidos a lo largo de la evolución humana (White, 1992; Fernández-Jalvo et al., 1996, 1999; Defleur et al., 1999; Bello et al., 2015).

La presencia de las marcas de corte es bastante frecuente en los yacimientos arqueológicos de todas las cronologías y pueden aparecer en toda clase de especies animales, desde grandes proboscidios (Yravedra et al., 2010, 2012) a micromamíferos, reptiles, aves, etc. (Blasco, 2008; Stringer et al., 2008; Blasco y Fernández-Peris, 2009, 2012; Finlayson et al., 2012).

Las marcas de corte se caracterizan por que presentan unas finas estrías con sección en V. Su longitud es variable, con múltiples y paralelos trazos en los valles internos de la marca, pudiendo presentar una orientación transversal o longitudinal y una anchura y profundidad variable dependiendo del tipo de herramienta con el que se realicen, la materia prima con la que se construyó dicha herramienta y la morfología ósea del fósil (Martin, 1909; Binford, 1981; Potts y Shipman, 1981; Bunn, 1982, 1983; Shipman, 1981, 1983; Shipman y Rose, 1983, 1984; Fisher, 1995;

Giacoboni y Patou Mathis, 2002; Domínguez-Rodrigo y Yravedra, 2009) (Figura 1). La presencia de microestriaciones internas, puede ser asociada a rasgos secundarios, tales como lengüetas, efectos del hombro o conos hertzianos (Martin, 1909; Binford, 1981; Potts y Shipman, 1981; Bunn, 1982, 1983; Shipman, 1981, 1983; Shipman y Rose, 1983, 1984; Fisher, 1995; Giacoboni y Patou Mathis, 2002; Domínguez-Rodrigo y Yravedra, 2009) (Figura 2).

Figura 1. Marcas de corte de descarnación con cuchillo sobre escapula.

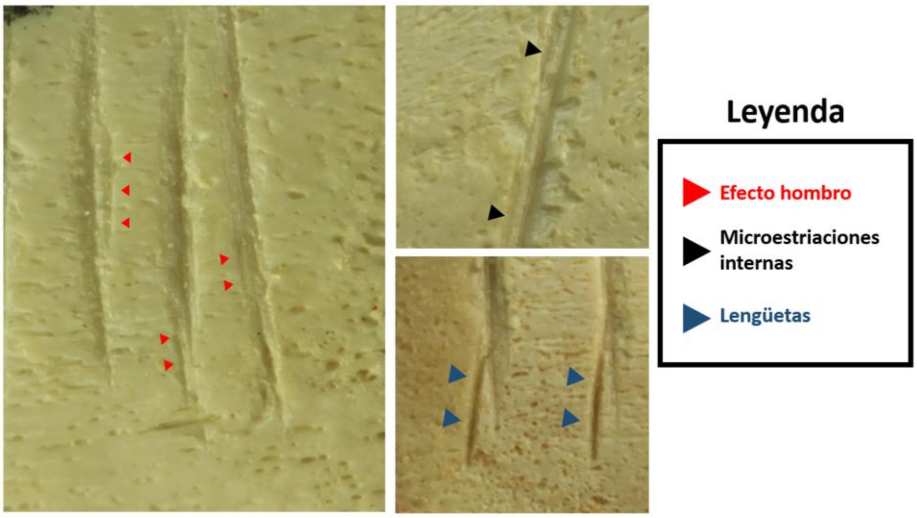

Figura 2. Elementos característicos que presentan algunas marcas de corte, tales como microestriaciones internas, lengüetas o efecto hombro.

El estudio de las marcas de corte puede abordarse desde diferentes perspectivas. En primer lugar, nos referiremos al estudio que se centra en analizar la frecuencia con la que aparecen las marcas de corte en una carcasa (Domínguez-Rodrigo, 1997). Dichas marcas, según tengan una frecuencia y una distribución esquelética determinada, pueden ser sintomáticas de comportamientos antrópicos primarios -cazadores- o secundarios -carroñeros- (Domínguez-Rodrigo, 1997; Capaldo, 1997). Arqueológicamente se han constatado, atendiendo a estos criterios, comportamientos cinegéticos en cronologías anteriores al millón de años en lugares como Olduvai, Swartkrans, Koobi Fora, Peninj, Atapuerca y Ain Hanech, (Domínguez-Rodrigo et al., 2002, 2007, 2009, 2014; Pickering et al., 2004; Huguet, 2007; Pobiner et al., 2009; Saladié et al., 2011; Sahnouni et al., 2012).

En segundo lugar, nos fijamos en el estudio de las marcas de corte con el objetivo de reconstruir actividades determinadas sobre restos óseos, realizadas por el hombre, como la descarnación, el desollado, el desarticulado, la evisceración, etc., de modo que, observando la distribución de dichas marcas, pueda saberse qué actividad se ha realizado sobre el fósil a estudio (Binford, 1981; Lyman, 1987; Nilsen 2001; Galan y Domínguez-Rodrigo, 2013). Atendiendo a esto mismo y a otra serie de variables, actualmente se está desarrollando un trabajo que trata de ver si se puede detectar una sistematización o no, en los procesos de aprovechamiento de carcasas y si es posible determinar tradiciones culturales en los procesos de aprovechamiento (López-Cisneros comentario personal).

La tercera vía de investigación, se centra en el análisis de las morfologías de las marcas de corte. Estas pueden ayudarnos a determinar con qué tipo de herramientas se procesan las carcasas o incluso si se utilizan unas materias primas u otras de forma preferente. Diversos investigadores han desarrollado algunos trabajos para discriminar con qué tipo de herramienta o materia prima se realizaban dichas marcas. Para ello han utilizado diversas técnicas microscópicas con el fin de analizar la morfología de la marca de corte, como la microscopía óptica, las lentes de mano y el SEM (Shipman, 1981, Olsen, 1988, Greenfield, 1999, 2004, 2006a, b), el microscopio binocular para imágenes de alta resolución (Domínguez-Rodrigo et al., 2009; De Juana et al., 2010; Marín-Monfort et al., 2014), las técnicas de imagen digital (Gilbert y Richards, 2000), la reconstrucción tridimensional (Bartelink et al., 2001), y una técnica microscópica reciente basada en el uso de microscopios digitales 3D, como el Alicona 3D Infinite

Focus Imaging Microscope (Bello y Soligo, 2008, Bello et al., 2009, Bello, 2011, Bonney, 2014) o el HIROX Digital Microscope KH-7700 (Boschin y Crezzini, 2012).

La mayoría de dichos análisis suponen la aplicación de metodologías microscópicas bastante sofisticadas y con un coste económico muy elevado. Además, presentan el problema de que para utilizar algunas de ellas, las muestras fósiles a analizar deben ser preparadas con anterioridad a su estudio. Esto supone un inconveniente si tenemos en cuenta que dichas muestras fósiles en la mayoría de las ocasiones no se encuentran en un estado de conservación óptimo, por lo que deben ser tratadas con extrema delicadeza debido a su fragilidad. Teniendo en cuenta su vulnerabilidad, muchas muestras no resistirían las preparaciones previas necesarias para ser analizadas directamente en los microscopios electrónicos. Para solventar estos inconvenientes, se han realizado en los últimos años réplicas de alta resolución de los fósiles originales. Dichas técnicas en ocasiones pueden producir daños irreparables sobre la superficie del fósil objeto de estudio, al utilizar un material de impresión inadecuado. Las primeras técnicas para la recreación de réplicas, utilizaban oro y materiales de alta conductividad y suponían la destrucción de la muestra. En la actualidad las siliconas o resinas son los materiales más utilizados, aunque pueden presentar problemas debido a que los datos que nos aportan no se ajusten a la resolución requerida, a la maleabilidad del material, etc.

Como consecuencia, el proceso de documentación que debe seguir el investigador en el tratamiento de cualquier resto fósil implica una gran inversión de tiempo, lo que hace que el estudio se reduzca a muestras muy pequeñas y por lo tanto estadísticamente poco significativas.

Con la aparición de los microscopios digitales 3D como el Alicona 3D Infinite Focus Imaging Microscope o el HIROX Digital Microscope KH-7700 no es necesaria la preparación de la muestra, ya que se puede realizar el estudio directamente sobre las muestras fósiles, lo que supone un gran avance en el campo de la investigación. Estos instrumentos realizan mediciones 3D mediante un barrido en *Z*, generando nubes de puntos 3D junto con el modelo digital de elevaciones (DEM). El software de estos instrumentos permite obtener perfiles de las marcas de corte, medir distancias, áreas, volúmenes, rugosidades, ángulos, etc. Todas estas características, hacen que sean instrumentos básicos en el estudio de las marcas de corte sobre hueso, debido a su gran potencia. Sin embargo y a pesar de que suponen un gran avance a la hora de reducir el tiempo de documentación, el gran inconveniente que presentan es que siguen resultando ser instrumentos con un coste económico muy elevado que necesitan de un técnico especialista para su utilización, lo que supone estar al alcance de muy pocos investigadores.

En un trabajo reciente de Ollé Cañellas (2012) se realizó un estudio comparativo de diferentes técnicas de microscopía en el análisis de muestras zooarqueológicas. El estudio se llevó a cabo comparando marcas de corte producidas por objetos líticos y marcas de diente de carnívoros y humanos. Los instrumentos utilizados para el análisis del trabajo anteriormente citado, han sido: una lupa binocular Olympus SZ11, el microscopio electrónico de barrido ambiental (ESEM) FEI Quanta 600, el Alicona 3D Infinite Focus imaging microscope y el Olympus extremo 3100 Laser Scaning Microscope. Los resultados mostraron que las diferentes técnicas son complementarias y dan buenos resultados. A pesar de todos estos avances, dichas técnicas siguen presentando el problema de que no profundizan sobre la variabilidad morfológica de las marcas de corte en función de los tipos de útiles o de las materias primas utilizadas. Algunos de los trabajos previos han tratado de profundizar en estos aspectos, pero con las diferentes limitaciones comentadas anteriormente, como es el escaso número de muestras analizadas, las fotografías defectuosas, etc. (Jones, 1980; Walker y Long, 1977; Greenfield, 1999, 2004; Walker, 1978).

Con el fin de paliar dichas limitaciones y con el objeto de crear una metodología apropiada y un marco de referencia adecuado nace la investigación desarrollada en esta Tesis Doctoral, cuyos objetivos describiremos en siguientes secciones.

Para llevar a cabo nuestros objetivos, hemos utilizado técnicas de reconstrucción tridimensional de objetos, nos referimos a la aplicación de técnicas fotogramétricas y técnicas laser. De cinco años a esta parte, se ha intensificado bastante el uso de dichas técnicas en el campo de la arqueología, cambiando la tendencia anterior a este periodo donde apenas eran utilizadas, siendo su aplicación principal el campo de la ingeniería.

La reconstrucción tridimensional de objetos y escenas arqueológicas para su documentación, estudio, análisis y divulgación ha sufrido una evolución constante en las últimas décadas. Se ha pasado de una documentación fotográfica, de croquis, de bocetos a mano alzada, de calcos -procedimiento altamente invasivo, ya que requiere de un contacto directo con el objeto-, de cartografía y topografía clásica, a unas nuevas técnicas innovadoras que han transformado profundamente su contexto de aplicación. Así mismo, el desarrollo de las nuevas geotecnologías y la Geomática han permitido un gran avance en la documentación de los yacimientos arqueológicos (López et al., 2010;

Moya-Maleno et al., 2015; Sabina et al., 2015; Fernández, 2016; Torres-Martínez et al., 2016), edificios con interés histórico (Cano et al., 2010; García et al., 2011; Coder y del Pino Espinosa, 2013; Farjas Abadía et al., 2015; Del Pozo et al., 2016), obras de ingeniería de la antigüedad (Guidi et al., 2009; Cobo et al., 2012; Cruzado et al., 2016), etc. Se ha conseguido transformar lugares y objetos reales a formato digital con rigor métrico y gran detalle, capaces de ser mostrados por la mayoría de equipos informáticos o mediante una web, una vez procesados los datos, obteniendo resultados muy visuales y gráficos para la difusión del patrimonio arqueológico y cultural y haciendo que la arqueología sea más atractiva para un público no experto (García-Morales y Cortina, 2015; Pierdicca et al., 2016). En consecuencia, se ha pasado de una información escasa en datos, a procesar gran cantidad de ellos en forma de nubes de puntos densas de objetos o escenarios, que permiten obtener una perspectiva espacial tridimensional detallada, precisa y de calidad. Esta documentación aporta información con propiedades métricas de un yacimiento u objeto arqueológico, de forma geométrica, estructural, dimensional y figurativa. De esta manera, se han mejorado los recursos de representación gráfica, disponemos de una planimetría más detallada y tenemos la opción de generar un modelo tridimensional del cual podemos obtener perfiles longitudinales y transversales, recorridos virtuales, cálculo de superficies, volúmenes, ortofotografías, monitorización del objeto a estudio para comprobar su deterioro, etc.
La documentación tridimensional se ha convertido en una herramienta indispensable para los arqueólogos a la hora de conservar, restaurar, modelar, estudiar, divulgar, etc. un yacimiento u objeto arqueológico.

En la actualidad, las geotecnologías que más se utilizan para la documentación de yacimientos y objetos arqueológicos son las técnicas fotogramétricas (García et al., 2011; Coder y del Pino Espinosa, 2013; García-Morales et al., 2015; García-Morales y Cortina, 2015; Moya-Maleno et al., 2015; Sabina et al., 2015) y las técnicas láser (Cano et al., 2010; López et al., 2010; Cobo et al., 2012; Fernández, 2016). Dichas técnicas son complementarias y se caracterizan porque su tecnología no es invasiva, es decir, no necesitan contacto físico directo con la superficie a reproducir y así la tecnología que emplean no daña el objeto a estudio.

El desarrollo de las nuevas tecnologías y su aplicación ha propiciado avances sustanciales en el empleo de las técnicas fotogramétricas y las técnicas laser gracias a la hibridación de sensores (Torres-Martínez et al., 2016), la visión computacional

(Förstner y Wrobel, 2016), la robustez de nuevos algoritmos y la automatización en los procesos empleados (González-Aguilera et al., 2016a, b).

La documentación en 3D ha evolucionado considerablemente, se ha pasado del estudio de objetos de grandes dimensiones (un edificio histórico, una fachada, etc.) para la obtención de perfiles, planos, cálculo de volúmenes, deformaciones, etc., a un interés más específico, donde se da más valor a una visión más minuciosa que se fija en aspectos más precisos del objeto a estudio.

Las técnicas fotogramétricas han experimentado un gran desarrollo gracias a la creación de nuevos algoritmos matemáticos provenientes de la visión computacional, propiciando una estabilidad y robustez a los métodos numéricos fotogramétricos. El desarrollo de software y de hardware en el ámbito informático, la fotografía digital, el procesamiento digital de imágenes junto con los algoritmos que utiliza la visión computacional que integra los métodos numéricos fotogramétricos de rango cercano, han permitido automatizar varios de los procesos del flujo fotogramétrico (e.g. auto-calibración, generación de modelos densos en nube de puntos, etc.), flexibilizar el trabajo -pudiendo utilizar cualquier tipo de cámara, no siendo necesario que sean cámaras métricas o semimétricas- y obtener resultados de gran calidad (reconstrucciones 3D con gran detalle) (González-Aguilera et al., 2016a, b). Estas técnicas han permitido la reconstrucción tridimensional y el análisis dimensional de escenarios y objetos (o detalles de estos) de manera automática, rápida y sencilla.

Todos estos avances, han propiciado que la fotogrametría sea accesible a cualquier tipo de usuario (no hace falta ser experto en la materia). También se ha conseguido abaratar los costes a la hora de obtener una documentación 3D.

Los escáner laser terrestres permiten la obtención masiva de información de grandes áreas en forma de nubes de puntos en un corto periodo de tiempo (e.g. yacimientos arqueológicos, edificios históricos, obras de ingeniería, etc.). La utilización de la mayor parte de los escáner laser para la documentación de objetos pequeños y zonas detalladas de estos resulta inapropiada, ya que suelen ser instrumentos grandes y pesados y su resolución no es la más indicada para realizar dichos trabajos.

No obstante, las técnicas laser también han experimentado un gran avance tecnológico con la aparición de nuevos instrumentos capaces de obtener nubes de puntos y modelos 3D de pequeñas áreas u objetos con alta precisión y resolución. Estos instrumentos se basan en nuevas tecnologías como los escáner de triangulación óptica y de luz estructurada, que son mucho más pequeños que los que se utilizan para la documentación del patrimonio arquitectónico, más manejables, más económicos y con mejores resoluciones. La utilización de este tipo de escáner se ha extendido mucho en este y otros campos de la ciencia y de la ingeniería (Cano et al., 2010; Calvache et al., 2011; Ramos et al., 2017).

En vista de todo ello, se podría decir que la utilización de las técnicas fotogramétricas y de las técnicas láser para la documentación tridimensional y la divulgación arqueológica se han convertido en herramientas indispensables para los arqueólogos, abriéndose paso en el mundo de la investigación arqueológica al resultar muy atractiva y asequible para ellos. Como se dice en el argot arqueológico "*excavar bien implica documentar mejor*", y evidentemente, una buena documentación implica plasmar todo lo que aparece en el escenario arqueológico en un momento concreto de una excavación y de una forma objetiva, sin alterar los materiales que aparecen en ella y dotando de un rigor y una exhaustividad métrica a la documentación obtenida. Por esto, el uso de dichas técnicas de documentación tridimensional son idóneas para la realización de estos estudios.

En los yacimientos arqueológicos, cuando se realiza una excavación, el proceso se comienza retirando las capas estratigráficas sedimentarias depositadas a lo largo de los diferentes períodos históricos que han acontecido en dicho lugar -en el orden contrario a su formación-, documentando y registrando los diferentes materiales de origen arqueológico que puedan ir apareciendo. Hay que tener en cuenta, que cada acción que se realiza sobre un yacimiento en el proceso de excavación no se puede revertir. Por ese motivo, es tan importante una documentación detallada de los materiales que van apareciendo en cada capa estratigráfica sedimentaria, para que posteriormente el investigador pueda saber cuál era su posición inicial e interpretar los datos obtenidos. De este modo, si el arqueólogo ha ido documentando la excavación desde el inicio hasta el final de la misma, es capaz de poder volver a visualizar virtualmente el momento del escenario que necesite estudiar. Por ejemplo, estas técnicas sirven para ver la distribución de los fósiles que han aparecido en una capa estratigráfica sedimentaria, comparar las diferentes capas, documentar el yacimiento al final de la excavación, monitorizar el deterioro de un yacimiento, documentar zonas de interés como mosaicos, muros, etc. (Gil et al., 2010; López et al., 2010; García et al., 2011; Vera et al., 2011; Ballester y Lillo, 2012; Coder y del Pino Espinosa, 2013; García-Morales et al., 2015; Moya-Maleno et al., 2015; Sabina et al., 2015; Farjas Abadía et al., 2015; Spanò et al., 2016).

El arqueólogo también puede obtener perfiles transversales y longitudinales de un yacimiento para calcular volúmenes, tomar medidas, realizar vistas generales en los momentos de excavación, realizar recorridos virtuales, monitorizar el yacimiento arqueológico a lo largo del tiempo, protegerlo contra una eventual destrucción, etc.

En la documentación tridimensional de objetos arqueológicos ya sean fósiles, cerámicas, esculturas, monedas, etc., o detalles concretos de estos objetos, las técnicas fotogramétricas y las técnicas láser han sido objeto de un importante calado, ya que han recortado los tiempos en la adquisición de los datos, han abaratado los costes y la documentación 3D ha resultado ser más exhaustiva y precisa (Zambanini et al., 2009; Cano et al., 2010; Fellner et al., 2011; Calvache et al., 2011; Falkingham, 2012; Kotoula y Kyranoudi, 2013; Fernández, 2016).

El uso de estas técnicas ha dado paso a nuevas aplicaciones que pueden ser útiles para solucionar problemas en el campo de la arqueología. Nosotros vamos a aplicarlas para la resolución de cuestiones tafonómicas y su influencia en el análisis de los procesos antrópicos.

Esta Tesis Doctoral lleva implícito el desafío de trabajar en un campo “nuevo” de investigación desde el punto de vista de la Geomática y más en particular de la fotogrametría. Nos referimos a la utilización de una metodología innovadora que nos permita realizar una documentación detallada 3D con precisiones submilimétricas de las marcas de corte sobre un resto fósil. Esta nueva metodología nace como alternativa al uso de las técnicas y metodologías microscópicas de alto coste que hasta ahora se han utilizado para realizar el estudio de las marcas de corte sobre hueso. En esta Tesis Doctoral se hace especial hincapié en resaltar el papel de “precisiones submilimétricas” debido, a que hemos tenido que idear nuevos métodos capaces de hacer reconstrucciones tridimensionales de calidad y resolución adecuada en estas escalas. El desafío es doble, no sólo por la creación de metodologías totalmente innovadoras, sino porque además implica una aplicación de dichas técnicas que en el campo de la arqueología no se ha realizado con anterioridad.

En definitiva, pretendemos ofrecer una metodología alternativa a las que actualmente se están utilizando en la documentación de las marcas de corte de origen antrópico, que aparecen en los restos fósiles arqueológicos estudiados. Dicha metodología tiene que permitir superar las limitaciones que generan la utilización de microscopios y aparatos especializados de difícil uso, alto coste y con poca accesibilidad para muchos equipos de investigación.

Con este trabajo se propone emplear las técnicas fotogramétricas más punteras para la obtención de modelos 3D y ofrecer una metodología precisa y fiable para este tipo de estudios.

Nuestra propuesta pretende diseñar una metodología innovadora que permita tratar muestras fósiles más amplias y a la vez reducir los costes analíticos.

Para ello usaremos las nuevas tecnologías basadas en técnicas laser o técnicas micro-fotogramétricas combinadas con la visión computacional. Estas incluyen el tratamiento de imágenes de alta resolución, con el objetivo de reconstruir en 3D las marcas de corte en hueso y nos permiten, ayudándonos de análisis estadísticos y morfométricos, analizar la micromorfología de éstas, atendiendo a criterios cualitativos y cuantitativos. Finamente y según los resultados obtenidos se planteará si estas técnicas pueden ser aplicadas a otro tipo de alteraciones óseas (e.g. como las marcas de diente, marcas de percusión, etc.).

2. Hipótesis del trabajo

Los análisis de las marcas de corte que aparecen en los restos óseos de los yacimientos arqueológicos se suelen estudiar desde diversas perspectivas. Los estudios centrados en las frecuencias y en la distribución de dichas marcas, tratan de discernir si los grupos humanos tuvieron accesos primarios –sintomáticos de comportamientos cazadores- o secundarios –sintomáticos de prácticas carroñeras-. Otros atendiendo a la posición de las marcas de corte en hueso tratan de reconocer actividades como el descarnado, el desarticulado, el eviscerado y/o el desollado, etc. En algunas ocasiones se determina o caracteriza cómo son todas estas actividades y qué metodología se emplea en el procesado de las carcasas animales. Pero muy pocas veces se analizan con detalle las morfologías de las marcas de corte para determinar qué tipo de útil se utiliza para aprovechar los animales, o incluso qué materias primas son más apropiadas para su procesado.

Los motivos por los que no se realizan estos análisis son varios:

- En primer lugar, hay que destacar el elevado coste que supone la aplicación de las técnicas microscópicas. Reaizar un análisis en detalle de una muestra considerable de las marcas de corte que aparecen en un yacimiento, implica la aplicación de técnicas microscópicas sobre dicho yacimiento, lo que como hemos expuesto implica grandes gastos. Además, dichas técnicas están disponibles sólo para unas pocas instituciones y al alcance de unos pocos equipos de investigación a la hora de realizar estos análisis debido a su elevado coste economico.

- En segundo lugar, para poder realizar un análisis en detalle de las marcas de corte y ver con qué tipo de materia prima o útil se han efectuado, son necesarios trabajos experimentales que analicen cómo son las marcas de corte realizadas con las materias primas presentes en el yacimiento. Por tanto, para llevar a cabo estos experimentos es necesario conocer perfectamente qué materias primas hay en el lugar y cuál es la fuente de aprovisionamiento, para poder replicar los útiles con los que realizar las marcas.

- En tercer lugar, no existen colecciones de referencia fotográficas que permitan caracterizar los distintos tipos de trazas producidos con diferentes materias primas, del mismo modo que tampoco hay marcos referenciales que puedan utilizase para establecer comparaciones.

- En cuarto lugar, determinar las marcas de corte implica tener un alto grado de especialización tafonómica previa en marcas de corte, y muchos equipos carecen de personal especializado para realizar dichas actividades.

Esta Tesis Doctoral pretende hacer frente a estos cuatro impedimentos. Por un lado, proponemos un nuevo tipo de análisis para realizar el estudio de las marcas de corte. Este nuevo método combina la información tafonómica derivada de la identificación de marcas de corte con estudios micro-fotogramétricos y de visión computacional que ofrezcan resultados de gran resolución para poder caracterizar adecuadamente dichas marcas. Por otro lado, para poder analizar los yacimientos objeto de esta Tesis Doctoral, proponemos realizar diversos experimentos con los que caracterizar la morfología de las marcas de corte según se utilicen diferentes materias primas. Una vez obtenidas estas muestras se generará un marco referencial que podrá incrementarse a medida que se vayan realizando nuevos análisis. Los estudios experimentales se efectuarán con las materias primas presentes en el yacimiento objeto de estudio. Finalmente y una vez caracterizado cada tipo de marca de corte, se contrastará con las marcas de corte identificadas en el registro arqueológico utilizando para ello distintos test estadísticos.

La finalidad de la investigación, es precisar qué finalidad tenía la utilización de las distintas materias primas que aparecen en los yacimientos, y determinar cuáles fueron las que se utilizaron en el procesamiento de los animales.

La diversidad de materias primas que aparecen en los yacimientos paleolíticos generan bastantes interrogantes, ya que ninguna tiene similares propiedades, y por consiguiente, parece que cada tipo podría estar asociado a diferentes actividades. A través de nuestro análisis trataremos de constatar cuales fueron las utilizadas en el procesamiento de los animales para su aprovechamiento cárnico y cuáles no. Por ejemplo, cómo la presencia de ciertos utensilios como los bifaces asociados a fauna, paradójicamente pueden no estar asociados a actividades de aprovechamiento animal (Yravedra et al., 2017b).

3. Objetivos

Los objetivos propuestos para la realización de esta Tesis Doctoral son:

Objetivo Principal

- Generar una metodología adecuada para realizar el estudio en detalle de las marcas de corte en hueso que vaya más allá de la mera observación macroscópica. Dicha metodología nos debe permitir identificar el tipo de materia prima utilizado para posibilitar el aprovechamiento de una carcasa. Identificar la materia prima utilizada en un yacimiento nos puede ayudar a reconstruir procesos económicos empleados por los grupos humanos del pasado. Por esto es importante saber con qué tipo de materias procesaban los recursos animales que aparecen en los yacimientos dichos grupos humanos. Al mismo tiempo, se pretende realizar dicho procedimiento utilizando técnicas de bajo coste y por tanto accesibles a toda la comunidad científica.

Objetivos secundarios

Desde una perspectiva metodológica:

- Comparar varias metodologías con el fin de realizar una estimación que nos permita precisar cuál es la más apropiada en tiempo, calidad, muestreo y costes.

- Generar una guía de buenas prácticas con la metodología analizada más eficaz.

- Valorar si los resultados de los distintos métodos pueden ser compatibles entre sí.

Desde una perspectiva analítica:

- Desarrollar un marco referencial apropiado que permita diferenciar las materias primas con las que se realizan las marcas de corte. En este caso se ha experimentado con metal, sílex, basalto, cuarcita de Olduvai y sílex y cuarcita de la Península Ibérica.

- Caracterizar las marcas de corte atendiendo a sus dimensiones y morfología (e.g. profundidad, anchura y longitud, sección, morfología, perfil, simetría de ángulos, etc.).

- Discriminar, con una aplicación más práctica, con qué tipo de materia prima se han realizado las marcas de corte de origen antrópico que aparecen en los restos fósiles arqueológicos estudiados en los yacimientos de Bell´s Korongo (BK) y Frida Leakey Korongo (FLK-WEST) del Pleistoceno inferior.

- Incorporar las técnicas de reconstrucción tridimensional al estudio de alteraciones tafonómicas, algo escasamente aplicado con anterioridad a la realización de este trabajo. Esto incluirá las marcas de corte objeto de estudio en esta Tesis Doctoral, pero se tratará de valorar si este tipo de técnicas pueden ser útiles en el estudio de otro tipo de alteraciones.

4. Estructura de la Tesis Doctoral

El núcleo central de la presente Tesis Doctoral corresponde a un compendio de siete artículos científicos publicados en revistas internacionales de impacto JCR y de un artículo científico publicado en una revista indexada. Esta Tesis Doctoral, titulada "*Implicaciones de la fotogrametría y de las técnicas láser en la identificación y caracterización de las trazas antrópicas sobre restos óseos en los yacimientos arqueológicos del Pleistoceno.*", se redacta en cumplimiento de las directrices de la Universidad de Salamanca, en su Reglamento de Doctorado (capítulo II artículo 14.1), sobre elaboración y defensa de la Tesis Doctoral, conforme al Programa de Doctorado interuniversitario en "Geotecnologías aplicadas a la Construcción, Energía e Industria" propuesto por las Universidades de Salamanca y Vigo, España, según el Real Decreto 99/2011, del 28 de enero, por el que se regulan las enseñanzas oficiales de doctorado en España.

Este trabajo, se organiza en cinco secciones que se especifican a continuación y que siguen una secuencia lógica de investigación de acuerdo con los objetivos establecidos:

Sección I: Metodológica

- **Micro-photogrammetric characterization of cut marks on bones.**

Maté-González, M. Á., Yravedra, J., González-Aguilera, D., Palomeque-González, J. F. & Domínguez-Rodrigo, M. 2015: Micro-photogrammetric characterization of cut marks on bones. Journal of Archaeological Science 62, 128-142. DOI: 10.1016/j.jas.2015.08.006.

- **Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones.**

Palomeque-González, J. F., **Maté-González, M. Á.**, Yravedra, J., San Juan-Blázquez, M., García Vargas, E., Martín-Perea, D. M., Estaca-Gómez, V., González-Aguilera, D. & Domínguez-Rodrigo, M. 2017: Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones. Journal of Archaeological Science: Reports 13, 60-66. DOI: 10.1016/j.jasrep.2017.03.033.

- **Assessment of statistical agreement of three techniques for the study of cut marks: 3D Digital Microscope, Laser Scanning Confocal Microscopy and Micro-Photogrammetry.**

Maté-González, M. Á., Aramendi, J., Yravedra, J., Blasco, R., Rosell, J., González-Aguilera, D. & Domínguez-Rodrigo, M. 2017: Assessment of statistical agreement of three techniques for the study of cut marks: 3D Digital Microscope, Laser Scanning Confocal Microscopy and Micro-Photogrammetry. Journal of Microscopy 0, 1–15. DOI: 10.1111/jmi.12575.

Sección II: Aplicación experimental al estudio de las marcas de corte

- **Micro-photogrammetric and morphometric differentiation of cut marks on bones using metal knives, quartzite and flint flakes.**

Maté-González, M. Á., Palomeque-González, J. F., 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 and Anthropological Sciences, DOI: 10.1007/s12520-016-0401-5.

- **Flint and quartzite: Distinguishing raw material through bone cut marks.**

Maté-González, M. Á., Yravedra, J., Martín-Perea, D. M., Palomeque-González, J. F., San Juan-Blázquez, M., Estaca-Gómez, V., Uribelarrea, D., Álvarez-Alonso, D., Cuartero, F., González-Aguilera, D. & Domínguez-Rodrigo, M. 2017: Flint and quartzite: Distinguishing raw material through bone cut marks. Archaeometry. DOI: 10.1111/arcm.12327.

Sección III: Aplicación sobre restos fósiles en yacimientos arqueológicos.

III. I. Aplicación sobre el estudio de marcas de corte en yacimientos

- **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.**

Yravedra, J., **Maté-González, M. Á.**, Palomeque-González, J. F., Aramendi, J., Estaca-Gómez, V., San Juan Blazquez, M., García Vargas, E., Organista, E., González-Aguilera, D., Arriaza, M. C., Cobo-Sánchez, L., Gidna, A., Uribelarrea del Val, U., Baquedano, E., Mabulla, A. & Domínguez-Rodrigo, M. 2017: 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. Boreas, DOI: 10.1111/bor.12224.

- **FLK West (Lower Bed II, Olduvai-Gorge, Tanzania): A new early Acheulean site with evidence for human exploitation of fauna.**

Yravedra, J., Diez-Martin, F., Egeland, C. P., **Maté-González, M. Á.**, Palomeque-González, J. F., Arriaza, M. C., Aramendi, J., García Vargas, E., Estaca-Gómez, V., Sanchez, P., Fraile, C., Duque, J., de Francisco Rodriguez, S., González-Aguilera, D., Uribelarrea, D., Mabulla, A., Baquedano, E. & Dominguez-Rodrigo, M. 2017: FLK West (Lower Bed II, Olduvai-Gorge, Tanzania): A new early Acheulean site with evidence for human exploitation of fauna. Boreas.

III. II. Aplicación sobre el estudio de otros procesos tafonómicos

- **On Applications of Micro-photogrammetry and Geometric Morphometrics to Studies of Tooth Mark Morphology: the modern Olduvai Carnivore Site (Tanzania).**

Arriaza, M. C., Yravedra, J., Domínguez-Rodrigo, M., **Maté-González, M. Á.**, García Vargas, E., Palomeque-González, J. F., Aramendi, J., González-Aguilera, D. & Baquedano, E. 2017: On Applications of Micro-photogrammetry and Geometric Morphometrics to Studies of Tooth Mark Morphology: the modern Olduvai Carnivore Site (Tanzania). Palaeogeography, Palaeoclimatology, Palaeoecology, DOI: 10.1016/j.palaeo.2017.01.036

Sección IV: Conclusiones

Sección V: Perspectivas futuras

Bibliografía

Sección I: Metodológica

La presente sección está formada por tres artículos que exponen la metodología desarrollada y empleada en el estudio de las marcas de corte sobre huesos.

En esta parte del trabajo se prueban y comparan las técnicas más punteras para la obtención de modelos 3D con precisiones submilimétricas, con el fin de proponer una metodología precisa y fiable para realizar este tipo de estudios. Esta Tesis Doctoral se basa en el uso de las nuevas tecnologías centradas en las técnicas laser y las técnicas micro-fotogramétricas, que junto con la visión computacional nos posibilitan el tratamiento de imágenes de alta resolución. En este proceso de investigación se comparan estas metodologías con el fin de efectuar una estimación de cuál es la más apropiada en tiempo, precisión, muestreo y costes, y así generar reconstrucciones tridimensionales de calidad y de resolución adecuadas a estas escalas.

En esta primera sección, también se propone una metodología para realizar el análisis y el estudio de las marcas de corte en hueso desde perspectivas estadísticas y morfométricas. Seleccionando un perfil característico de la marca de corte y siguiendo los pasos que se proponen, se pueden obtener y sintetizar todas las medidas que se utilizan para la clasificación de dichas marcas de corte.

Por último, en este apartado, se compararan los resultados obtenidos mediante técnicas microscópicas (que son las que se utilizan en estos últimos años para la reconstrucción virtual y el análisis de marcas de corte) y técnicas micro-fotogramétricas (propuestas en esta Tesis Doctoral). El fin de este estudio, es evaluar la resolución y los resultados que generan dichas técnicas y comprobar si las técnicas micro-fotogramétricas producen resultados estadísticamente similares o no a las técnicas microscópicas, y si son igualmente válidas para el estudio de las marcas de corte sobre hueso.

Artículo 1**:**

Título: **Micro-photogrammetric characterization of cut marks on bones.**

Año de publicación: 2015

Revista: Journal of Archaeological Science 62, 128-142.

DOI: 10.1016/j.jas.2015.08.006

Autores: **Maté-González, M. Á.**, Yravedra, J., González-Aguilera, D., Palomeque-González, J. F. & Domínguez-Rodrigo, M.

Resumen:

La tafonomía en estos últimos años ha resultado ser una disciplina crucial para el estudio de los yacimientos arqueológicos prehistóricos. Entre los diferentes procesos tafonómicos que pueden ir asociados a la acción humana, las marcas de corte han suscitado un gran interés en el ámbito arqueológico, ya que estas evidencias halladas en huesos fosilizados aportan mucha información a la explicación del comportamiento alimenticio humano. Su representación, frecuencia, distribución y significado han sido ampliamente utilizados para la interpretación de dichos yacimientos. Llegados a este punto, la correcta definición de estas marcas y la información que se puede obtener de ellas resulta crucial en los estudios tafonómicos que llevan a cabo los arqueólogos (e.g., la identificación de las materias primas utilizadas en el procesado cárnico de un animal). Diversos investigadores han utilizado diferentes técnicas microscópicas para poder observar mejor las marcas de corte. Estas técnicas presentan buenos resultados pero también algunos problemas o inconvenientes, tales como: los costes de estos equipos son muy elevados estando sólo al alcance de unos pocos equipos de investigación o de centros especializados y además es necesaria una capacitación técnica para su uso o recurrir a un técnico especialista.

En consecuencia, en este estudio se pretende buscar técnicas alternativas, que mediante la utilización de una metodología accesible y de bajo coste, permita el análisis de la micromorfología de las marcas de corte, ofreciendo un alto grado de resolución suficiente como para analizar la morfología, la profundidad, la anchura, los ángulos y la sección de las marcas de corte directamente sobre el hueso estudiado.

Para ello se han explorado y testeado técnicas microscópicas, técnicas fotográficas, técnicas laser y técnicas micro-fotogramétricas combinadas con la visión computacional.

El método micro-fotogramétrico, que se basa en la fotografía oblicua y que usa una cámara réflex con objetivo macro para la toma fotográfica y emplea el proceso de auto-calibración en el proceso de la reconstrucción tridimensional, es el que depara en todos los casos de estudio analizados los mejores resultados, ajustándose a las precisiones y a unos tiempos cortos en la captura y post-procesamiento de los datos.

En este artículo se examinan un total de quince marcas de corte realizadas con un cuchillo de acero inoxidable en tres diáfisis de hueso largo y en una escápula de

cordero. Como las marcas de corte en hueso tienen una longitud variable y la morfología de la sección de la marca cambia en función del punto elegido en el modelo tridimensional, es necesario analizar estadísticamente la marca de corte para probar que partes son igualmente diagnósticas morfológicamente. En este artículo se demuestra que cualquier perfil tomado en la marca de corte entre el 30% y el 70% es válido.

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Micro-photogrammetric characterization of cut marks on bones

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ABSTRACT

In the last few years, the study of cut marks on bone surfaces has become fundamental for the interpretation of archaeological sites and prehistoric butchery practices. Due to the difficulties in the correct identification of cut marks, many criteria for their description and classifications were suggested. This article presents an innovative methodology which supplements the microscopic study of cut marks. Despite the benefits of using scanning electron microscopy (SEM) for the two-dimensional identification of these marks, it has a number of drawbacks such as the high costs and, consequently, the limited sample studied. In this article, a low-cost technique for the analysis of cut mark micromorphology from a tri-dimensional perspective is introduced. It provides a high-resolution approach to cut mark characterisation such as morphology, depth, width, and angle estimation as well as section determination, measured directly on the marks on bones. Macro-photogrammetry records quantitative and qualitative information which can be statistically processed with standard multivariate and geometric morphometric tools.

1. Introduction

Lartet (1860), Peale (1870), Lartet and Christy (1875) and Martin (1909) were pioneers in the study of cut marks in the late 19th and early 20th centuries. They observed the presence of marks in archaeological assemblages, but did not engage into any fine-detailed analysis of them. During the 20th century, several scholars observed, classified and described cut marks, amongst which the seminal studies by White (1952, 1953, 1954, 1955), Binford (1981), Bunn (1982) or Shipman (1981) should be emphasized. In the last few years, the analysis of cut marks has become extremely relevant in the interpretation of the archaeological record, as it has offered evidence to interpret such diverse behaviours as hunting by Olduvai hominins 1.8 Myr ago (Bunn and Kroll, 1986; Domínguez-Rodrigo et al., 2007), or the replacement of lithic butchery tools by metal ones during the Holocene (Greenfield, 1999, 2004).

In the past 20 years, cut mark analysis has become more sophisticated. Experimental recreation of cut mark frequencies and their anatomical location on ungulate carcasses were considered (Capaldo, 1997; Domínguez-Rodrigo, 1997), as well as replications of different butchery processes such as filleting, dismembering or evisceration (Binford, 1981; Lyman, 1987; Nilsen, 2001; Galán and Domínguez-Rodrigo, 2013). Others studies focused on discriminating cut marks from other processes such as trampling (Shipman, 1981; Shipman and Rose, 1983; Behrensmeyer et al., 1986; Domínguez-Rodrigo et al., 2009), or characterizing the raw material of the cutting tool: flint, obsidian, metal, quartz (Olsen, 1988; Greenfield, 1999, 2004, 2006a, b; Bello and Soligo, 2008; Yravedra et al., 2009), shell (Choi and Driwantoro, 2007), or bamboo (Spennerman, 1990; West and Louys, 2007). Other research addressed cut mark morphology according to stone tool type (i.e. simple or retouched flakes, handaxes) (Walker, 1978; Shipman and Rose, 1983; Bello et al., 2009; Domínguez-Rodrigo et al., 2009; De Juana et al., 2010; Galán and Domínguez-Rodrigo, 2013).

In these studies, cut mark morphology analyses were restricted to optic microscopy, hand lenses and SEM (Shipman, 1981; Olsen, 1988; Greenfield, 1999, 2004, 2006a,b; Smith and Brickley, 2004; Lewis, 2008), binocular microscope for high resolution pictures (Domínguez-Rodrigo et al., 2009; De Juana et al., 2010; Marín-Monfort et al., 2014), digital imaging techniques (Gilbert and Richards, 2000), three-dimensional reconstruction

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(Bartelink et al., 2001; During and Nilsson, 1991; Kaiser and Katterwe, 2001), 3D digital microscope (Boschin and Crezzini, 2012; Crezzini et al., 2014), and a recent technique based on the use of Alicona 3D Infinite Focus Imaging microscope (Bello and Soligo, 2008; Bello et al., 2009; Bello, 2011; Bonney H., 2014).

These techniques basically recorded the main features of cut mark morphology (i.e. V-section of cut mark grooves) including variable length, width and depth depending on tool type, its raw material and bone morphology, inasmuch as the presence of internal microstriations which may be associated with secondary features such as barbs, shoulder effects or Hertzian cones (e.g. Martin, 1909; Binford, 1981; Shipman, 1981; Shipman and Rose, 1983). Although in most cases cut marks were described following two-dimensional observations, Bello and co-authors have used Alicona to interpret cannibalistic and funerary practices (Bello and Soligo, 2008; Bello et al., 2011a, 2015; Schulting et al., 2015), as well as to study teeth and the use of the mouth as a third hand (Hillson et al., 2010 Bello et al., 2011b). They also applied this method to the interpretation of engraved bones and antlers (Bello et al., 2013a) and the use of these materials as retouch tools and hammers (Abrams et al., 2014; Bello et al., 2013b). Boschin and Crezzini (2012) exemplified their technique in the analysis of archaeological collections to distinguish cut-marks produced by metal from stone-tool damage. The application of 3D technology was also used for engraved pottery (Montani et al., 2012) and prehistoric art (Güth, 2012).

The present article describes a methodology which overcomes the limitations implied in the use of microscopes -i.e. restricted

Table 1
Technical specifications, usage and classification of the tools used.

Tool	Classification	Working	Technical specifications
Trinocular stereoscopic microscope with image sensor.	Passive sensor	An image sensor is installed in the third observation channel of the microscopy and its optical is used as the objective.	• Euromex NOVEX AR Trino (Continuous Zoom 1X a 4X) + Reflex Camera Nikon D5100 (sensor CMOS de 23.6 × 15.6 mm de 16.2 MP) + Camera Adapter T-System. • Motic DM-39C–N9GO A (Fixed Zoom 2X a 4X) with digital camera included (CMOS 1/2″ 3 MP, Pixel matrix 2048 × 1536). • Motic SMZ-143 (Continuous Zoom 1X a 4X) + Reflex Camera Nikon D5100 (sensor CMOS of 23.6 × 15.6 mm of 16.2 MP) + Camera Adapter T-System.
Microscopic multifocal motorized with high-resolution digital camera included	Passive sensor	It corrects the limited field depth of macro-photography when the focal length, focus distance and diaphragm opening are reduced. The user has to focus the furthest and the nearest point of the object. The microscopic function takes those points as a reference and automatically makes a sequence of intermediate images of the same scene, changing the focus point. Finally, it joins those images and generates a single clear photography with each element focused in a precise way.	• Leica M 205C (Continuous Zoom 0.7X a 160X) + Sensor DFC 450 (CCD − ICX282 8.7 × 6.5 mm, 5 MP).
Digital portable microscopic USB	Passive sensor	The images obtained are only visible by computer software. A photograph collection is needed.	• Digital portable microscopic USB Celestron (Continuous Zoom 1X a 4X y 15x fixed). Digital camera (CMOS 1.3 MP, Pixel matrix 1280 × 1024).
Reflex camera + Reverse mounting adapter of objective	Passive sensor	The reverse mounting adapter of objective is an accessory placed between the body of the camera and the objective, which is placed in a reverse position. It simulates a macro objective.	• Reflex camera Nikon D5100 (sensor CMOS of 23.6 × 15.6 mm of 16.2 MP, pixel size of 4.78 μm) + Objective 18–55 mm + Reverse mounting adapter of objective of 52 mm.
Reflex camera + Extension Tubes of Objective	Passive sensor	The extension tubes of the objective are an accessory placed between the body of the camera and the objective, reducing the minimum lens focus distance. It simulates a macro objective.	• Reflex camera Nikon D5100 (sensor CMOS of 23.6 × 15.6 mm of 16.2 MP pixel size of 4.78 μm) + Objective 18–55 mm + Aluminium Extension Tubes of Objective of lengths 12 mm, 20 mm y 36 mm.
Reflex camera + Close-Up lens Macro Filter Set	Passive sensor	The close-up lens macro is a filter screwed at the end of the objective which increasing the image area, creating a loupe effect. It simulates a macro objective.	• Reflex camera Nikon D5100 (sensor CMOS de 23.6 × 15.6 mm of 16.2 MP pixel size of 4.78 μm) + Objective 18–55 mm + 52 mm Close-Up lens Macro Filter Set of 1X, 2X, 4X and 10X.
Reflex camera + Macro Objective	Passive sensor	Sensor system of images invented to focus at short distances, enlarging the elements focused three to four times. The result is high quality photographs.	• Reflex camera Canon EOS 50D (Sensor CMOS (APS-C) of 22.3 × 14.9 mm of 15.1 MP, pixel size of 4.7 μm) + Objective SIGMA 50 mm 1 2.8 dg macro
Metrological Laser Scanner	Active sensor	Metric recorder of an object with coordinates. As result, a 3D model is obtained.	• Hexagon Metrology Absolute Arm 7325SI. Measuring Range 2.5 m. Probing Point Repeatability ±0.079 mm. Probing Volumetric Accuracy ±0.069 mm. Scanning System Accuracy ±0.042 mm. Max. Point acquisition rate: 50.000 Points/s. Line Rate: 30 Hz. Accuracy (2 sigma): 30 μm).
Structured Light 3D Scanner	Active sensor	System made up of a camera, a projector and a calibration board. It must be first calibrated placing the camera and the projector in 15° and 25° angles towards the calibration board. The projection must cover the calibration board completely. The scale of the calibration board is specified in the software, the exposition of the camera is adjusted and the focus of the camera and the projector are verified in the tools. It needs to be calibrated as well. The camera and the projector must be fixed. The object substitutes the calibration board. The pictured is scanned and a 3D points cloud or a 3D model of the object is made.	• David Structured Light Scanner SLS-2. Scan size: 60 −500 mm. Resolution: Up to 0, 1% of scan size (down to 0.06 mm). Scanning time: One single scan within a few seconds. Mesh density: Up to 1,2000,000 vertices per scan = ACER K132 + Structured Light Projector + DAVID USB CMOS Monochrome Camera with Lens + DAVID Structured-Light Calibration Panels Set.

Table 2
Advantages and disadvantages of the different tools and techniques and if the method is appropriate or not.

Tools	Description of the technique	Advantages	Disadvantages	Conclusion
Trinocular stereoscopic magnifier with sensor of images.	Production of macro photography to use macro-photogrammetric techniques with vertical photograph captures.	+ The photographic sensor uses the microscopy optical as objective, taking detail photographs.	+ Very poor photograph quality if the object has relief. Due to the limited field depth, the photography looks badly focused. + It is not possible to take convergent photographs; they can only be perpendicular to the object. + It is a static tool: the object should be moved (not practical for photogrammetry). + Short distance between the object and the tool to make a right 3D reconstruction. + Static, heavy and difficult to use tool. + In some cases, bad illumination of the object. + Data collection and processing protocols are slow.	+ Perpendicular photograph capture at short distance does not generate quality geometric models. + Unfocused photograph of objects with relief. + The 3D models obtained do not have relief, they are flat. NO APPROPRIATE TECHNIQUE
Microscopic multifocal motorized with high-resolution digital camera included	Production of macro photography to use macro-photogrammetric techniques with vertical photograph captures.	+ Specific tool to make high detail and quality photographs of flat objects and elements with relief due to the internal system which creates a focused photograph from different joined images.	+ It is not possible to take convergent photographs; only pictures perpendicular to the object are taken. + It is a static tool: the object should be moved (not practical for photogrammetry). + Short distances between object and tool to make a good 3D reconstruction. + The pixels of the photograph generated by the microscopy are modified due to the matching images. + Static, heavy and difficult to use tool. + Data collection and processing protocols are slow.	+ Perpendicular photograph capture at short distance does not generate quality geometric models. + In the areas where the photography has a bigger alteration of pixels, the reconstruction of 3D models shows deformations. + The 3D models obtained do not have relief, they are flat. NO APPROPRIATE TECHNIQUE
Digital portable microscopic USB	Production of macro photography to use macro-photogrammetric techniques with vertical and convergent photograph captures.	+ High detail photographs can be made. + It is possible to see the microscopic image directly on the computer screen. + Effective.	+ Very low photographic quality, bad focus due to the little depth of field. + Short distance between the object and the tool to make a right 3D reconstruction. + Data collection and processing protocols are slow.	+ Digital images do not have enough quality. + Very distorted models, with no quality. NO APPROPRIATE TECHNIQUE
Reflex camera + Reverse mounting adapter of objective	Production of macro photography to use macro-photogrammetric techniques with vertical and convergent photograph captures.	+ Low cost macro photograph. + Good quality of image.	+ For convergent photography, the focus is bad in the extreme cases. + For perpendicular photography, the distance between the object and the tool is still small to get a good 3D reconstruction. + Data collection and processing protocols are slow.	+ In the cases of parallel photographs, the short distance capture of the object cannot generate good quality geometric models. + In the case of convergent photography, the photography capture with the biggest perspective has a focus problem. + The 3D models obtained do not have relief, they are flat. NO APPROPRIATE TECHNIQUE
Reflex camera + Extension Tubes for the Objective	Production of macro photography to use macro-photogrammetric techniques with vertical and convergent photograph captures.	+ Low cost macro photograph.	+ Poor photographic quality. + When the objective is opened out, little light is available, so better lighting is necessary. + For convergent photographs, the focus is not appropriated for the extremes. + For perpendicular photographs to the base line, the distance between the object and the tool is still small to get a good 3D reconstruction. + Data collection and processing protocols are slow.	+ Digital images of objects with relief do not have enough quality due to limited focus. + In the cases of parallel photographs, the short distance capture of the object cannot generate good quality geometric models. + In the case of convergent photography, the photography capture with the biggest perspective has a focus problem. + The 3D models obtained from vertical photography do not have relief, they are flat. + The 3D models obtained from the convergent photographs become distorted. NO APPROPRIATE TECHNIQUE
		+ Low cost macro photograph.		

Reflex camera + Close-Up lens Macro Filter Set	Production of macro photography to use macro-photogrammetric techniques with vertical and convergent photograph captures.		+ Increased objective optical distortion, more anomalies. + Poor photographic quality. + For convergent photograph, the focus is unsuitable for the extremes. + For perpendicular photographs to the base line, the distance between the object and the tool is still small to get a good 3D reconstruction. + Data collection and processing protocols are slow.	+ Digital images of objects with relief do not have enough quality due to limited focus. + In the cases of parallel photographs, the capture at a short distance to the object cannot generate good quality geometric models. + In the case of convergent photographs, the collection at a large perspective has a focus problem. + The 3D models obtained from vertical photographs do not have relief, they are flat. + The 3D models obtained from the convergent photographs become distorted. NO APPROPRIATE TECHNIQUE
Reflex camera + Macro Objective	Production of macro photograph to use macro-photogrammetric techniques with vertical and convergent photograph captures.	+ Good quality of image. + For convergent photograph, the focus is good in the extremes.	+ For perpendicular photographs, the distance between the object and the tool improves considerably but it is still not sufficient to get a good 3D reconstruction.	+ In the cases of parallel photographs, the capture at a short distance to the object cannot generate good quality geometric models. + The 3D models produced from vertical photographs do not have relief, they are flat. NO APPROPRIATE TECHNIQUE + Convergent photography: high quality 3D models. APPROPRIATE TECHNIQUE
Metrological Laser Scanner	Production of high-resolution 3D models for the use of computational vision techniques.	+ Fast data collection protocol. It is possible to scan many pieces in a short time. + The scanning provides a metric model to scale.	+ Poor scan resolution.	+ The metrological laser scanner does not have enough resolution to capture cut marks. NO APPROPRIATE TECHNIQUE
Structured Light 3D Scanner	Production of high-resolution 3D models for the use of computational vision techniques.	+ Once the system is configured, the data collection protocol is fast. It is possible to scan many pieces in a short time. + The scanning provides a metric model to scale. + Low cost system.	+ It is difficult to get good results. Significant differences between outputs.	+ Difficult to find an effective protocol for data collection, which allows obtaining always a good result without variations among different captures. NO APPROPRIATE TECHNIQUE

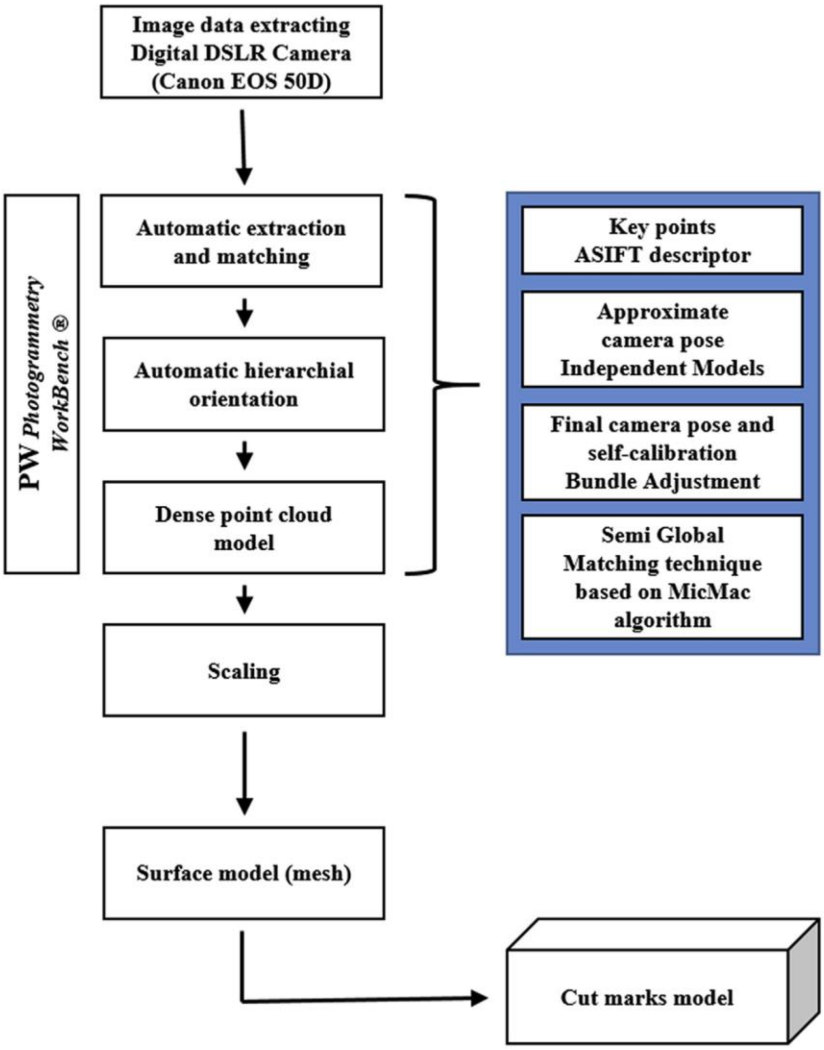

Fig. 1. Macro-photogrammetric protocol to generate the 3D model of cut marks.

access due to high costs-by reducing analytical costs and, consequently, enlarging the sample to be tested. This technique incorporates treatment of high-resolution images with macro-photogrammetry and computer visualisation for tri-dimensional reconstruction of cut marks on bones. These micromorphological data are later analysed in both qualitative and quantitative terms.

2. Materials and methods

In this study, different criteria were used (Table 1) for a morphometrical characterisation of cut marks on bones. A total of 15 cut marks made with a stainless steel knife (Molybdenum Vanadium C 0.5 CR 14 MO 0.5 VA 0.25) on three long bone diaphysis and a lamb scapula were examined with macro-photogrammetric and computer vision techniques which included different tools of microscopic and laser technology (Table 1). A single right-handed person performed all the marks on lamb fresh bones. The bones were later cleaned by boiling in tap water for the analyses.

The preliminary analysis showed that macro-photogrammetric techniques using photographs taken with a reflex camera with a macro function provided a better resolution than alternative approaches. Table 2 presents the advantages and disadvantages for each of the techniques used.

2.1. *Macro-photogrammetric technique*

A three-dimensional model of quantitative and qualitative information about the cut mark was drawn from a series of images and following an easy application protocol (see subsection 2.1.1.). Some of the most critical steps in the process were the orientation of the images regarding their angular and spatial positions, and the determination of the internal parameters of the camera (self-calibration). Fig. 1 illustrates the different steps involved in the macro-photogrammetric and computational vision method used for 3D modelling of images.

2.1.1. *Image capture protocol*

The methodology for macro-photogrammetric analysis required placing a millimetre scale next to the cut mark to be photographed so as to provide a precise measurement reference (Fig. 2).

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. Several tests of different exposition and opening of the diaphragm were needed to verify the optimal parameters, as well as to calculate the distance needed for a good definition of the cut mark. Both the exposition moment of the camera and lighting remained constant during the image data capture.

For the capture of images, two kinds of configurations were followed: the parallel photography method (Fig. 3a) and the oblique and convergent photography method (Fig. 3b). The distance between the camera and the object was approximately 100–120 mm.

Parallel photography was composed of images captured at a perpendicular axis regarding the object photographed. Each picture was parallel, creating coplanar plans to the object with a minimum overlapping of 80% (Fig. 3a). Convergent photography, on the other hand, required taking photographs which converge in a point and do not need to be parallel (Fig. 3b). In this case, overlapping of photographs must be complete (100%). Furthermore, the two adjacent camera stations had to be generally placed at an intersection angle of about 15° to the object.

Both configurations presented certain advantages and disadvantages. The main advantage of parallel photogrammetry was to avoid the perspective becoming distorted. On the other hand, ray intersection geometry was rather poor, but it was especially important to have a good parameter when reconstructing depth and relief. Convergent photogrammetry offered a better ray intersection geometry, although the perspective became somewhat distorted, affecting the automatic reconstruction process.

The number of photographs for each model depended on the size and features of the relevant cut marks on the bone, as well as its position on either a flat or a bended plane.

Once the photographs had been taken, they were processed so as to generate a 3D model for each mark. Consequently, the photographs were treated with a photogrammetric reconstruction software such PW (Photogrammetry Workbench) (González-Aguilera et al., 2013) or another reconstruction software such Agisoft photoscan. PW software followed the workflow presented in Fig. 1.

2.1.2. *Hierarchical orientation of images and self-calibration*

The automatic orientation of the angular and spatial position of the images required the previous drawing and matching of certain features (i.e. points of interest). In particular, a variation in the algorithm SIFT (Scale-Invariant Feature Transform) (Lowe, 1999) called ASIFT (Affine Scale Invariant Transform) (Morel and Yu, 2009) had to be added, to improve the data collection by, for instance, considering two additional affinity parameters for perspective control (i.e. the two perspective angles of the optical axis of the camera, φ (tilt) angle and ϖ (axis) angle (Equation (1))). Therefore, the ASIFT algorithm was useful for the manipulation of images in perspective, frequent in these cases. The result was a keypoint algorithm, which presented no variation regardless of scale, rotation, movement, or main deformations caused by the different perspectives of the images. The following expression summarises the resulting affine scale invariant transformation:

$$\mathbf{A} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} = H_\lambda R_1(\kappa) T_1 R_2(\varpi) = \lambda \begin{bmatrix} \cos\kappa & -\sin\kappa \\ \sin\kappa & \cos\kappa \end{bmatrix} \cdot \begin{bmatrix} t & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos\varpi & -\sin\varpi \\ \sin\varpi & \cos\varpi \end{bmatrix} \quad (1)$$

where **A** was the affine transformation with the λ scale, and κ the rotation of the optical axis (swing). The perspective parameters for the inclination of the optical axis of the camera were represented by φ (tilt) = across $(1/t)$, the angle between the optical axis and the normal of the image plane and ϖ (axis), the azimuth angle between the optical axis and a fixed vertical plane.

Taking into account the data generated by ASIFT, the image was oriented following a double procedure involving computer vision and photogrammetry to reach an approximate orientation of the images in an arbitrary coordinates system (computer vision) which could be later refined and improved to assemble the images (photogrammetry).

It was necessary to relatively orientate the images by using independent models, as well as calculating the fundamental matrix using the Longuet–Higgins algorithm (Longuet-Higgins, 1987). One of the main advantages of the fundamental matrix was its independence from the scene pictured. Therefore, the matrix could be calculated from the corresponding point in the image, regardless the internal parameters and original approximations of the cameras. The fundamental matrix was defined by the following Equation (2):

$$\mathbf{x}'^T \mathbf{F} \mathbf{x} = 0 \quad (2)$$

For each pair of matching points $x_i \leftrightarrow x'_i$ (8 minimum), Equation (3) calculated the fundamental matrix. More specifically, by writing $x = (x,y,1)$ and $x' = (x',y',1)^T$, each matching point created a linear equation,

$$x'xf_{11} + x'yf_{12} + x'f_{13} + y'xf_{21} + y'yf_{22} + y'f_{23} + xf_{31} + yf_{32} + f_{33} = 0 \quad (3)$$

It should be noted that this procedure was completely automatic compared with other photogrammetric approaches where the user needed to set the initial approximations and know the internal parameters of the camera. Secondly, once the relative angular and spatial position of the images were established, a comprehensive bundle adjustment was made by an iterative and least-squares process based on the co-linearity condition (Kraus, 1993) and adding the object coordinates for fully georeferencing the images (Equation (4)). Object coordinates were incorporated into the

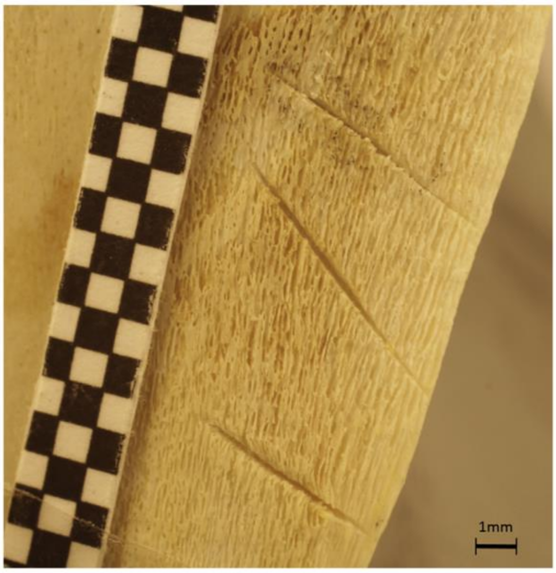

Fig. 2. Photography of cut marks. The millimetre reticule can be seen next to the marks.

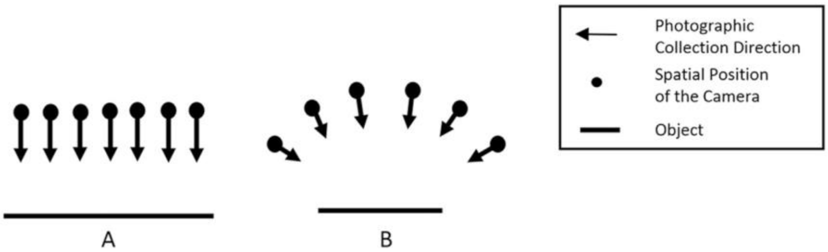

Fig. 3. (a) Parallel photography capture. (b) Oblique and convergent photography capture.

orientation process from the millimetre reticule placed on the object (Fig. 2). When the internal calibration parameters (i.e. focal length, principal point and lens distortion) were unknown, this step adds to the equation the camera calibration parameters as unknown quantities (self-calibration).

$$(x - x_0) + \Delta x = -f\frac{r_{11}(X - S_X) + r_{21}(Y - S_Y) + r_{31}(Z - S_Z)}{r_{13}(X - S_X) + r_{23}(Y - S_Y) + r_{33}(Z - S_Z)}$$
$$(y - y_0) + \Delta y = -f\frac{r_{12}(X - S_X) + r_{22}(Y - S_Y) + r_{32}(Z - S_Z)}{r_{13}(X - S_X) + r_{23}(Y - S_Y) + r_{33}(Z - S_Z)} \quad (4)$$

where x and y were the image coordinates; X, Y, Z were the object control points coordinates, corresponding to the millimetre reticule placed on the object which placed the scale in the scene; r_{ij} were the rotation matrix elements, including the rotation of the camera; S_X, S_Y, S_Z were the object coordinates of the camera viewpoints; f was the main distance; x_0, $y_{0,}$ the main point coordinates of the image; and ΔX, ΔY represented the translations due to the radial and tangential distortion of the lens. In case these internal parameters of the camera were unknown, they were thus indicated (self-calibration) in the calculation of the global adjustment.

2.1.3. Dense model generation

The dense matching process started with the robust image orientation, based on the semi-global matching technique (SGM) (Hirschmuller, 2005; Deseilligny and Clery, 2011). The projective Equation (5) generated a dense model from the identification of a 3D coordinate per pixel.

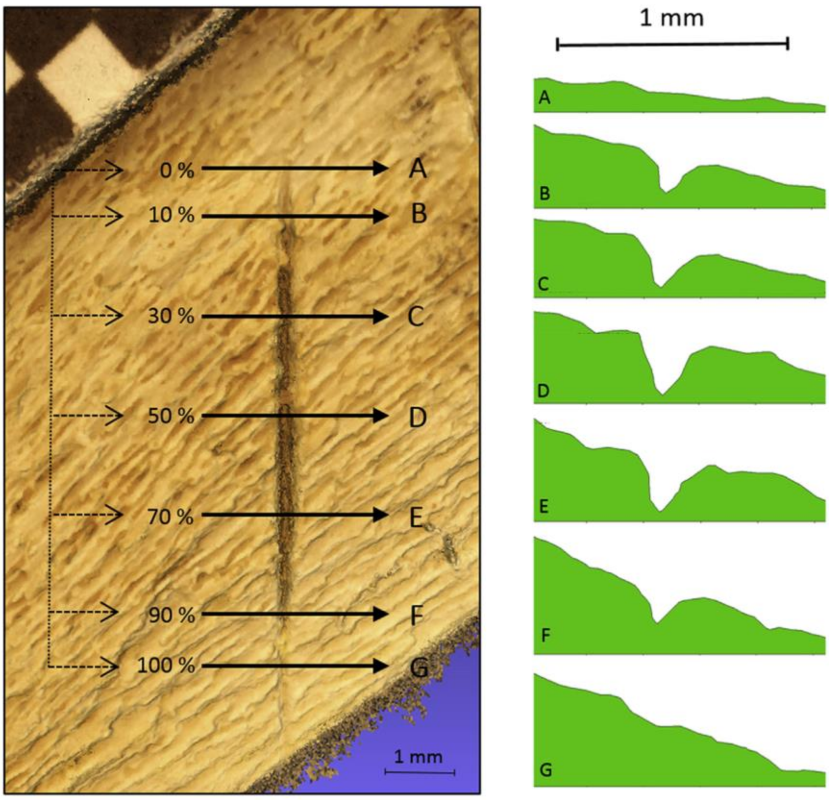

Fig. 4. Cut marks analysis: cross sections from different relative positions along the cut mark.

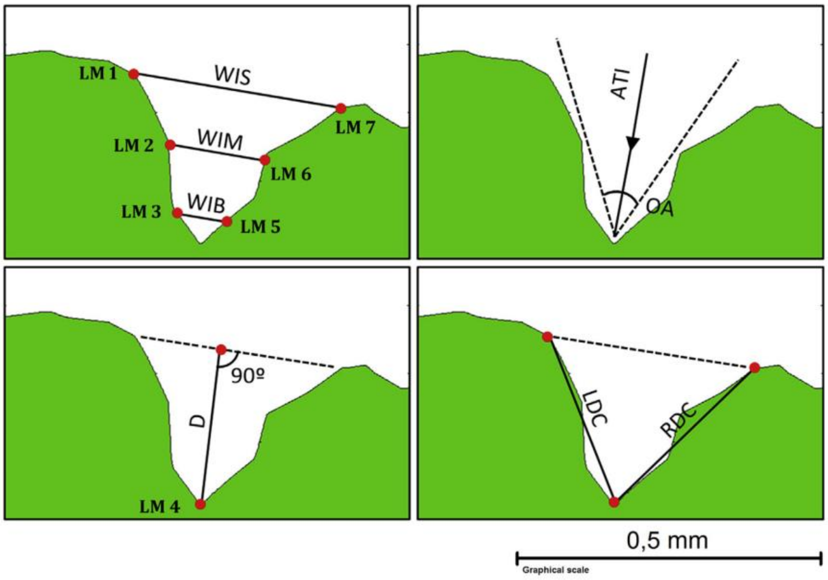

Fig. 5. Representation of the measures for each mark cross-profile (following Table 3), and the location for the 7 landmarks used in the morphometric analysis (LM 1–7).

$$x_k = C(D(R_i(X_k - S_i))) \quad (5)$$

Where X was the 3D point; x was the point corresponding to the image; R was the camera rotation matrix; S was the camera projection centre; C was the internal calibration function; D was the lens distortion function, and the subscripts k and i were related to point and image, respectively.

The SGM process consisted of minimising an energy function (6) through the eight basic directions a pixel could follow (every 45°). This function was integrated by a cost function (i.e. M, pixel matching cost), which reflected the similarity of the pixels in two images (x and x'), together with the incorporation of two restrictions, P_1 and P_2, which showed the possible presence of outliers in the SGM process. In addition, a third constraint was added to the SGM process: epipolar geometry, derived from photogrammetry (Hartley and Zisserman, 2003). It restricted the search space per pixel in order to reduce the huge computational cost involved. As a result, it generated a dense model with multiple images, obtaining optimal processing times.

$$E(D) = \sum_x \left(M(x, D_x) + \sum_{x' \in N_x} P_1 T[|D_x - D_{x'}| = 1] + \sum_{x' \in N_x} P_2 T[|D_x - D_{x'}| > 1] \right) \quad (6)$$

Table 3
Measurements used to characterize the cut mark sections as described in Fig. 5.

WIS	Width of the incision at the surface
WIM	Width of the incision at the mean
WIB	Width of the incision at its bottom
OA	Opening angle of the incision
D	Depth of the incision
LDC	Left depth of the incision convergent
RDC	Right depth of the incision convergent
ATI	Angle of the tool impact

Where $E(D)$ was the energy function to be minimised on the basis of the disparity (parallax) between homologous features; the function C (pixel matching cost) evaluated the level of similarity between the pixel p and its counterpart q through the disparity D_p, while P_1 and P_2 corresponded to two restrictions aimed to avoid outliers in the dense matching process due to the disparity of one single pixel or many of them respectively.

2.2. Cut mark analysis

The completion of 3D models of cut marks was followed by a thorough analysis of the morphology and section of the traces. The 3D model allowed an infinite number of sections to be defined along the groove. This method, however, offered an objective selection of sections to compare among different marks. Each cut mark was divided into equidistant sections, comprising the 0% (A), 10% (B), 30% (C), 50% (D), 70% (E), 90% (F) and 100% (G) of the mark length (Fig. 4). Sections corresponding to B, C, D, E and F were subsequently measured. The first and last sections (A and G) were not included as they represented the beginning and end of a mark.

Measurements were expressed as independent variables, following Bello et al. (2013a) (Fig. 5). These measurements indicated the thickness, depth, and angles of the mark (see Table 3).

2.3. Statistical analysis

In order to test if there was any difference in the several measurements, a variance analysis (ANOVA) was applied. However, this analysis required previously the use of Bartlett's test in order to confirm that variance was homogeneous throughout the sample. Those values indicating significant variation among section types were thus subjected to multiple variance analysis (MANOVA) for the comparison of metric variables and the determination of the mean values for the five-section grouping proposed.

As an independent confirmation method, a principal component analysis (PCA) was also performed to study the overlapping of the five subsamples (as per mark section) beyond their differences in

136 M.Á. Maté González et al. / Journal of Archaeological Science 62 (2015) 128–142

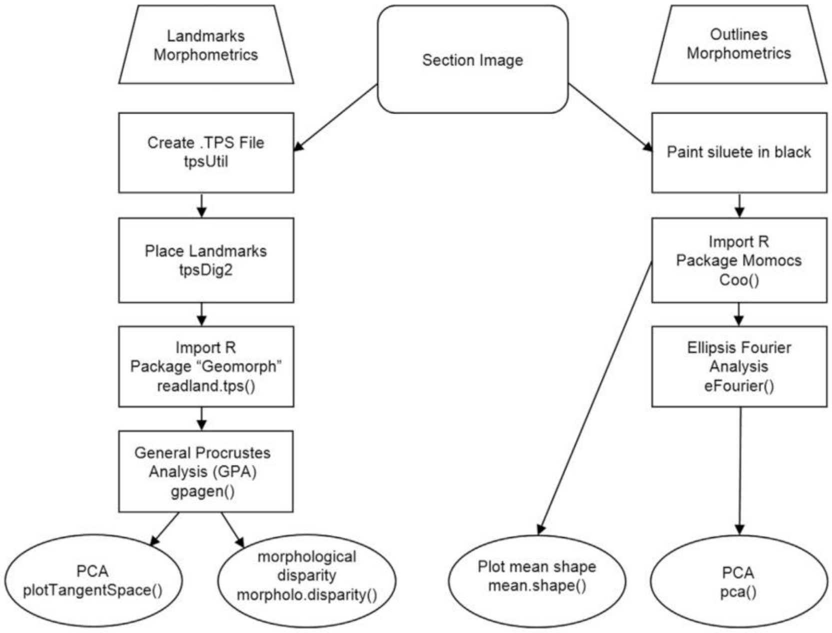

Fig. 6. Diagram of the morphometric analysis used in this research.

Table 4
Main technical data from the 3D models created. GSD (9) (Ground Sample Distance) is the equivalence of the image pixel on the ground, D is the distance to the object, F is the focal length and pixel size p.

	Fieldwork						
	Measurements cut marks (mm)				N° of images	Distance max/min (m)	Fieldwork (minutes)
	Cut mark	Length	Width	Height			
Model 1	1	7.221	0.297	0.222	7	0.12/0.1	12
Model 2	2	3.952	0.321	0.205	6	0.12/0.1	12
Model 3	3	5.229	0.418	0.142	13	0.12/0.1	12
	4	4.994	0.419	0.191			
Model 4	5	3.577	0.245	0.136	5	0.12/0.1	12
Model 5	6	3.811	0.261	0.216	5	0.12/0.1	12
Model 6	7	3.353	0.635	0.295	11	0.12/0.1	12
Model 7	8	2.377	0.645	0.233	9	0.12/0.1	12
Model 8	9	3.471	0.652	0.109	11	0.12/0.1	12
	10	3.214	0.624	0.142			
Model 9	11	7.251	0.673	0.255	9	0.12/0.1	12
Model 10	12	6.082	0.308	0.156	9	0.12/0.1	12
Model 11	13	2.267	0.53	0.221	9	0.12/0.1	12
Model 12	14	2.265	0.447	0.11	10	0.12/0.1	12
Model 13	15	3.757	0.304	0.178	5	0.12/0.1	12

	Laboratory work							
	Tie points	N° matching points	GSD (mm)	Photogrammetric adjustment error (mm)	Scaling error (mm)	Total error (mm)	Resolution (mm/pixel)	Laboratory work (minutes)
Model 1	24,928	2,772,921	0.0103	±0.0076	±0.0166	±0.0183	±0.0094	35
Model 2	16,603	7,771,843	0.0103	±0.0086	±0.0166	±0.0187	±0.0047	30
Model 3	43,622	4,255,532	0.0103	±0.0089	±0.0166	±0.0188	±0.0093	65
Model 4	12,459	2,273,766	0.0103	±0.0088	±0.0166	±0.0188	±0.0096	35
Model 5	4592	2,101,687	0.0103	±0.0183	±0.0166	±0.0247	±0.0095	35
Model 6	1515	3,127,808	0.0103	±0.0198	±0.0166	±0.0258	±0.0217	60
Model 7	1683	3,062,299	0.0103	±0.0192	±0.0166	±0.0254	±0.0204	40
Model 8	1941	3,317,796	0.0103	±0.0166	±0.0166	±0.0235	±0.0221	60
Model 9	1468	3,289,203	0.0103	±0.0142	±0.0166	±0.0218	±0.0201	40
Model 10	1682	3,707,530	0.0103	±0.0178	±0.0166	±0.0243	±0.0093	40
Model 11	1955	2,773,400	0.0103	±0.0616	±0.0166	±0.0231	±0.0234	40
Model 12	1904	2,555,692	0.0103	±0.017	±0.0166	±0.0237	±0.0242	45
Model 13	5523	1,857,879	0.0103	±0.0128	±0.0166	±0.0209	±0.0095	35

$GSD = \frac{p \cdot D}{f}$ (9).

mean values per metric variables which resulted from the previous variance analysis. Biplots with 95% confidence ellipses were used.

ANOVA and MANOVA tests were performed with R (www.r-project.org) software (Core-Team, 2013). Furthermore, PCA is included in the R library FactoMineR (Lê et al., 2008). Plotting of the PCA results with confidence ellipses was made with the ggplot2 R library.

A geometric morphometric analysis was performed as well as a GPA as a supplementary alternative to the multivariate metric analysis (Fig. 6). Two morphometric approaches were used here: landmarks and outlines. Seven identical landmarks per section were considered from each mark using the tpsUtil (v. 1.60) and tpsDig2 (v. 2.1.7) programs. The location of the seven landmarks responded to the measures considered for the statistical analysis, as seen in Fig. 5. Thus, LandMark 1 (LM) 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 end of the mark. LM4 was at the very end, and LM5, LM6 and LM7, in an opposed position to LM3, LM2 and LM1, (Fig. 5). The resulting tps file was imported to R and analysed via the "geomorph" library (Sherratt, 2014).

A general Procrustes analysis (GPA) was later applied on the landmark data, followed by a PCA. 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 morphometric analysis of the outlines used the R library Momoocs. The mean shape per section was established (with the mean. shape function) and a Fourier Analysis was subsequently used to analyse outline shape similarities and differences.

3. Results

The definition of an appropriate optimum-resolution alternative method for cut marks analysis demanded a series of tools and techniques, as described in Table 1.

3.1. Results of the macro-photogrammetric method

As mentioned above, a large variety of analytical tools were reviewed in order to find a technique for generating high quality 3D models to be used in the geometrical study of cut marks on bones. Each of them followed some protocols and presented specific characteristics which determined their potential. Furthermore, the revision indicated that in most cases they did not seem suitable for this kind of analysis due to either data collection or post-processing time.

The macro-photogrammetric method, which was based on oblique photography and uses a reflex camera with macro lens, showed the best results in all study cases analysed, meeting the precision and short capture and post-processing time requirements. Particularly, an average time of 50 min was required to analyse a single cut-mark. Further details about the time required at field and laboratory work is described in Table 4. The accuracy for this method has already been demonstrated in other

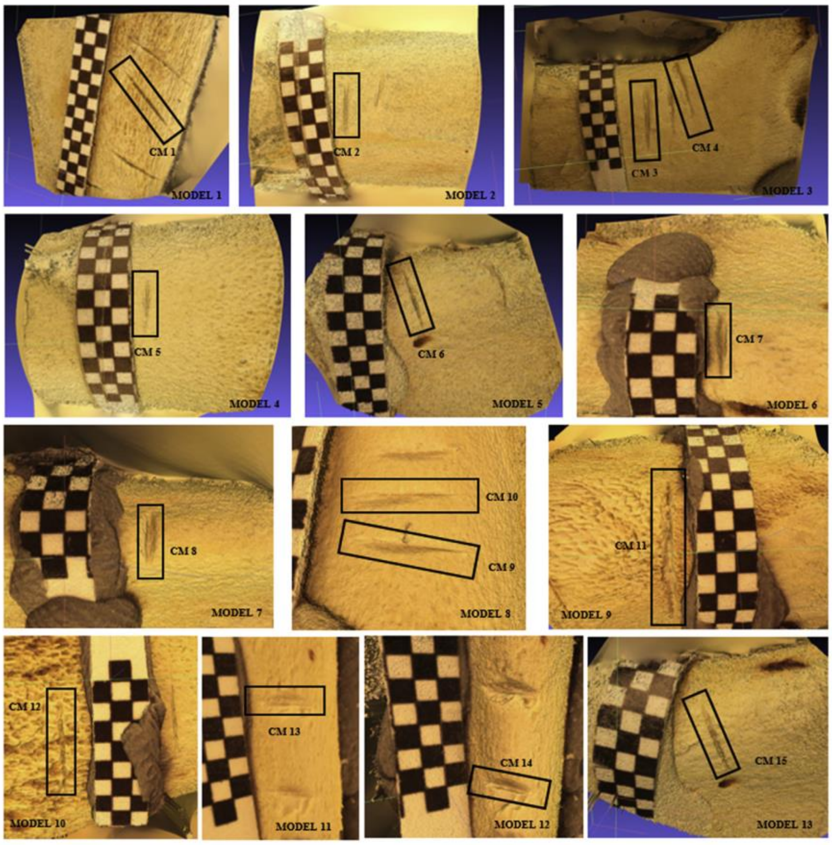

Fig. 7. 3D models of the different bones and cut marks analysed, where CM = Cut Mark.

Table 5
Measurement, distances (mm) and angles (°), from the sections of the different cut marks on bones, according to Bello et al., 2013a. See Fig. 5.

		WIS	WIM	WIB	OA	D	LDC	RDC	ATI
Mark 1	B	0.2481	0.1098	0.0393	61°	0.1492	0.1986	0.1889	76°
	C	0.324	0.1275	0.0472	63°	0.1862	0.2498	0.2439	79°
	D	0.3211	0.177	0.0471	56°	0.2484	0.2916	0.3	83°
	E	0.3129	0.1438	0.0479	54°	0.2311	0.2675	0.2918	79°
	F	0.279	0.1089	0.0333	64°	0.1434	0.1889	0.212	77°
Mark 2	B	0.3475	0.1948	0.0947	91°	0.1446	0.1999	0.2545	89°
	C	0.3147	0.2097	0.0514	74°	0.1804	0.1996	0.2883	84°
	D	0.3141	0.1728	0.0544	60°	0.233	0.2673	0.2964	84°
	E	0.3009	0.1726	0.038	64°	0.2018	0.2391	0.2656	86°
	F	0.328	0.2226	0.0559	91°	0.1456	0.234	0.2053	89°
Mark 3	B	0.3103	0.2162	0.0953	114°	0.0983	0.1703	0.1974	94°
	C	0.4004	0.2589	0.1037	109°	0.1154	0.3174	0.1559	104°
	D	0.4267	0.3008	0.1055	100°	0.148	0.3339	0.1953	99°
	E	0.5369	0.3502	0.136	111°	0.1639	0.3896	0.2461	95°
	F	0.4139	0.2931	0.1141	108°	0.111	0.3383	0.1457	104°
Mark 4	B	0.4749	0.3023	0.1003	120°	0.0942	0.1308	0.3956	88°
	C	0.3936	0.2016	0.0345	77°	0.1813	0.2167	0.3292	85°
	D	0.3876	0.1854	0.0285	71°	0.212	0.2491	0.333	80°
	E	0.4286	0.227	0.1174	92°	0.1788	0.2524	0.3077	81°
	F	0.4106	0.2687	0.0404	102°	0.1576	0.2177	0.3044	77°
Mark 5	B	0.223	0.1493	0.0314	105°	0.0838	0.1525	0.1271	90°
	C	0.2476	0.1492	0.0329	91°	0.0995	0.2097	0.1168	93°
	D	0.2754	0.1633	0.0541	70°	0.1726	0.2402	0.2038	80°
	E	0.2393	0.107	0.027	74°	0.1351	0.2041	0.1603	89°
	F	0.241	0.1517	0.0323	109°	0.0787	0.1703	0.1196	80°
Mark 6	B	0.1091	0.0529	0.0105	48°	0.0911	0.0976	0.1174	96°
	C	0.3396	0.17	0.0587	63°	0.2089	0.3044	0.2401	100°
	D	0.3551	0.1563	0.0408	59°	0.2352	0.2905	0.299	95°
	E	0.3245	0.225	0.0355	69°	0.2032	0.311	0.2218	95°
	F	0.1748	0.1064	0.017	65°	0.1299	0.1644	0.1501	98°
Mark 7	B	0.3545	0.196	0.0497	122°	0.0849	0.1531	0.2424	91°
	C	0.552	0.3648	0.0757	90°	0.2567	0.3135	0.4519	84°
	D	0.6967	0.3452	0.0655	80°	0.3053	0.4389	0.4886	86°
	E	0.6553	0.353	0.0829	81°	0.3219	0.3857	0.5479	82°
	F	0.6292	0.3388	0.0653	102°	0.2272	0.3879	0.3883	86°
Mark 8	B	0.4103	0.2656	0.0639	125°	0.106	0.2146	0.2476	125°
	C	0.6859	0.4249	0.1421	105°	0.2486	0.4159	0.4313	129°
	D	0.6682	0.4121	0.1118	97°	0.261	0.345	0.5138	127°
	E	0.5809	0.3713	0.1321	107°	0.1893	0.2801	0.4196	130°
	F	0.5324	0.3149	0.1029	97°	0.1961	0.1961	0.4275	129°
Mark 9	B	0.1674	0.1091	0.0306	111°	0.0519	0.0811	0.1173	84°
	C	0.6806	0.3783	0.0485	147°	0.0998	0.3383	0.371	85°
	D	0.6356	0.3326	0.0902	136°	0.1146	0.3166	0.3592	84°
	E	0.6408	0.3403	0.0236	135°	0.1132	0.2726	0.4089	84°
	F	0.6424	0.3847	0.1697	130°	0.1103	0.242	0.4411	76°
Mark 10	B	0.3516	0.2191	0.0926	132°	0.0675	0.2522	0.1279	105°
	C	0.5541	0.3022	0.0943	130°	0.127	0.2891	0.3205	94°
	D	0.6814	0.3794	0.0593	128°	0.1549	0.3617	0.3869	95°
	E	0.6359	0.3444	0.0538	127°	0.1429	0.3102	0.3879	91°
	F	0.4812	0.2364	0.065	131°	0.093	0.2065	0.3111	86°
Mark 11	B	0.7498	0.3907	0.0895	104°	0.2391	0.4865	0.4043	104°
	C	0.6689	0.3197	0.0894	105°	0.2372	0.4622	0.3611	100°
	D	0.6094	0.3568	0.0662	95°	0.253	0.4072	0.3851	100°
	E	0.7392	0.3595	0.0868	93°	0.2759	0.5499	0.3815	101°
	F	0.6255	0.3859	0.0631	117°	0.1652	0.4256	0.2859	103°
Mark 12	B	0.3769	0.2229	0.0418	133°	0.0708	0.1484	0.2566	91°
	C	0.2912	0.1642	0.0275	83°	0.1408	0.2062	0.1987	102°
	D	0.3502	0.1784	0.0266	79°	0.1572	0.2112	0.2613	90°
	E	0.283	0.1894	0.0131	81°	0.1689	0.2041	0.2254	92°
	F	0.326	0.1932	0.042	129°	0.0707	0.2124	0.1445	96°
Mark 13	B	0.6149	0.2853	0.0478	83°	0.2286	0.3839	0.3823	99°
	C	0.4792	0.2814	0.0655	83°	0.2109	0.3853	0.2628	99°
	D	0.5129	0.2873	0.0675	73°	0.2401	0.3652	0.3379	108°
	E	0.599	0.3399	0.1411	95°	0.2118	0.476	0.2732	97°
	F	0.3021	0.1504	0.0439	120°	0.0755	0.2116	0.129	81°
Mark 14	B	0.4627	0.2856	0.1435	94°	0.1018	0.1149	0.4219	85°
	C	0.5765	0.3941	0.1164	95°	0.1111	0.1153	0.5567	88°
	D	0.4038	0.2816	0.1153	90°	0.1202	0.1278	0.3775	87°
	E	0.362	0.2211	0.1356	99°	0.0973	0.0973	0.3306	83°
	F	0.3745	0.237	0.094	142°	0.0612	0.1658	0.228	89°
Mark 15	B	0.1695	0.132	0.0321	87°	0.0823	0.1074	0.0129	78°
	C	0.333	0.1681	0.0684	60°	0.2023	0.2335	0.3025	77°
	D	0.3808	0.1867	0.0536	70°	0.1969	0.2262	0.3337	82°
	E	0.3133	0.1583	0.0484	83°	0.1353	0.1911	0.2238	88°
	F	0.3209	0.146	0.0238	120°	0.0741	0.1437	0.2112	88°

micro-photogrammetric experiments (Rodriguez-Martin et al., 2015a, b).

Fig. 7 shows the 3D modelling of the 15 cut marks analysed, while Table 4 presents the technical data of the 3D models created. Regarding cut marks measurements, Table 5 explains the dimensional analysis according to the data in Fig. 5.

In order to estimate the total error (ε) associated to the dimensional analysis of cut marks using the macro 3D models generated, the error propagation had to be analysed by quadratic error propagation. Two main sources of errors were identified during the macro image-based modelling process proposed: first, the error coming from the photogrammetric adjustment, known as a posteriori error (ε_a); and second, the error corresponding to the scaling of the 3D model which was manually defined by the user. The latter was established as (7) $\sqrt{2}\times$ pixel size (s), considering the error associated to the electronic micrometre (destination error) ($\varepsilon_m = 0.01$) as well. Hence, the scaling error was calculated as:

$$\varepsilon_s = \sqrt{\varepsilon_m^2 + 2s^2} \quad (8)$$

More details about this error budget were outlined in Table 4.

As shown in the tables presented *supra*, some of the measurements of the cut mark sections (Table 5) were smaller than the total error of the models (Table 4). These measurements were only considered as estimates for the statistical analysis and did not imply any significant modification to the morphologic study of the cut mark.

The marks yielded a typical morphology with a V section, a straight groove and variable dimensions, with maximum lengths differing in each mark and ranging between 7.25 mm in mark 11, and 2.27 mm in marks 13 and 14. Mark width and depth were also variable (Table 5). The tool used in these experiments (metal knife) conditioned the absence of microstriations parallel to the principal axis of the mark (Figs. 2 and 4). However, given the variability of marks produced in this experiment, certain specifications were due regarding the differences and the possibility that some measurements of width, depth or other variables described in Fig. 5 were conditioned by the location (type of section) analysed. This was a key question as the results determined the most diagnostic sections to characterise cut mark dimensions and morphometry. Consequently, the most informative sections could be used to compare marks generated with raw materials or kinds of tools in the future.

The Bartlett test showed homogeneity of variance, which allowed the application of the ANOVA test (Fig. 8). This yielded significant differences in four variables, OA, D, LDC and RDC, which were selected for the MANOVA analysis. In turn, the MANOVA test confirmed the inter-section metric differences and allowed the recognition of inter-section differences via a pairwise comparison (Fig. 9). It showed that mark width, regardless the section chosen, was homogeneous; therefore the widths of WIS, WIM and WIB were similarly diagnostic of the mark morphology in each section. On the contrary, OA, D, LDC y RDC showed differences according to the section considered.

A PCA demonstrated that, despite the differences in mean values for the five sections, the overall confidence intervals of each section overlapped, making their identification extremely difficult. Only sections B and F had a differing tendency, probably due to greater

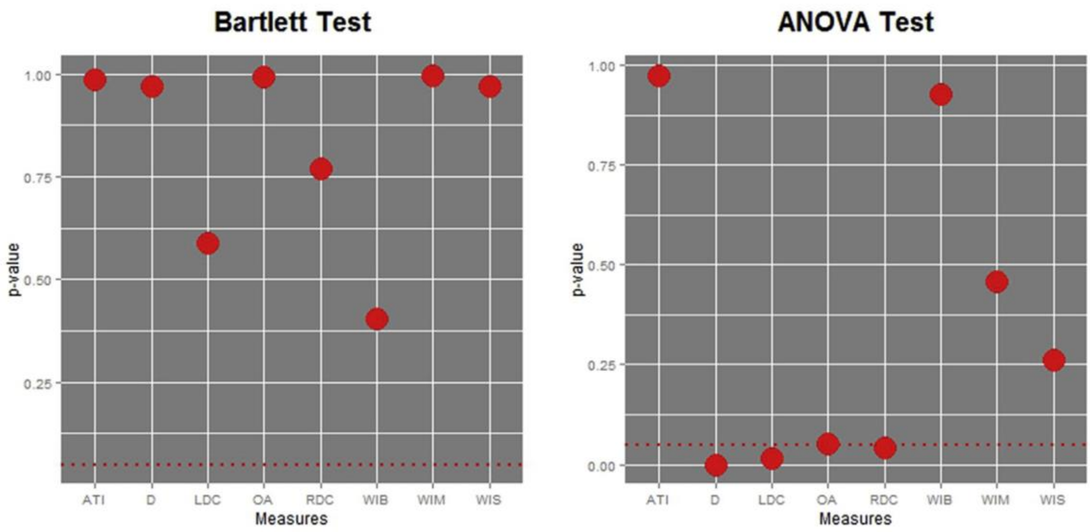

Fig. 8. Results of the Bartlett and ANOVA tests.

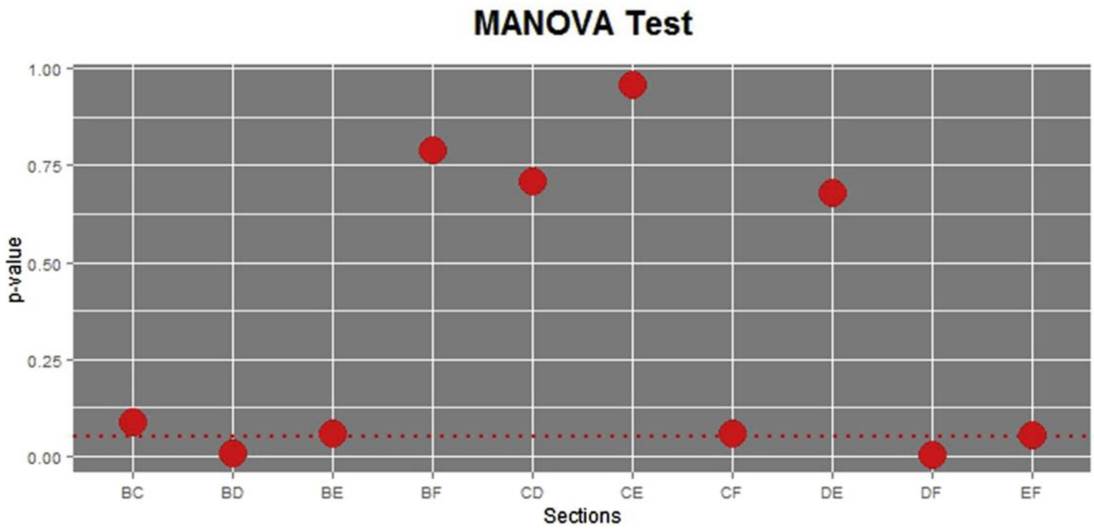

Fig. 9. Result of the MANOVA test.

variability at the beginning and end of the cut marks. The central sections yielded more homogeneous morphologies; therefore sections, C, D and E were the best ones to characterise the section morphology of the mark (Fig. 10).

The landmark geometric morphometric analysis reported an even more intense overlapping of section morphology, being virtually impossible to differentiate each of the five segments (Figs. 11 and 12). It was further confirmed by the morphological disparity analysis. None of the sections presented a significant p-value; it meant that no significant morphological differences were detected. Similar results were provided by the outline geometric morphometric analysis, as seen in the PCA graphics (Fig. 13).

Despite the seemingly variability reflected in the measurements of the different cut marks (Table 5), the tests performed indicated such small differences that they could hardly be considered significant (Figs. 11–13). This was especially true in the case of section width, variables WIS, WIM y WIB and the rest of the variables in sections C–E, which were slightly divergent from sections B and F. So, for a confident comparison of cut marks made with different raw materials or tool types, the values for the sections between 30% and 70% of the mark length would be the most representative one.

4. Conclusions

This article described the tools, methods and results from the geometric study of cut marks on bones by applying macro-photogrammetric and computer vision techniques. This proposal aimed to develop a low cost methodology precise enough to

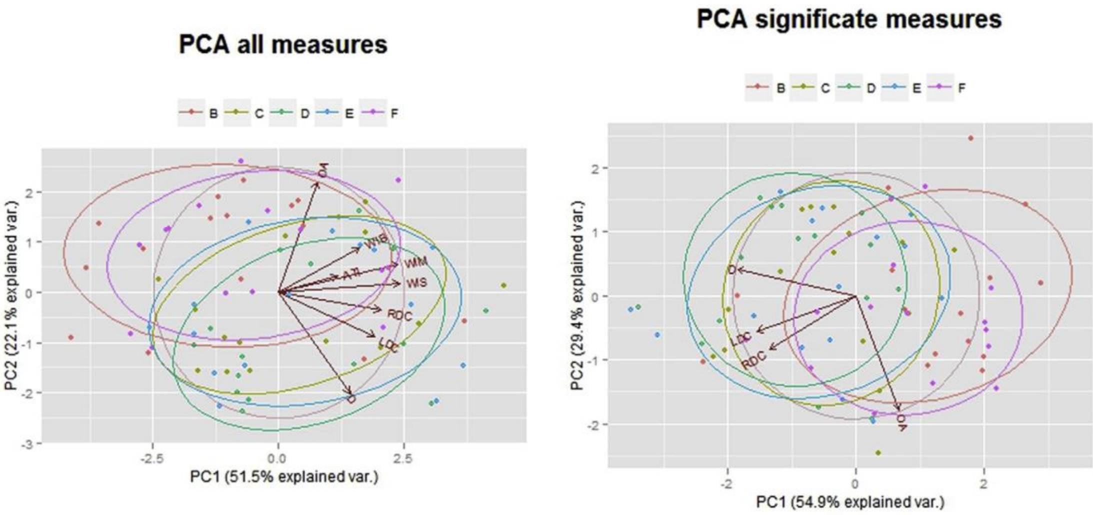

Fig. 10. PCA tests with all measures (left) and only representative measures (right).

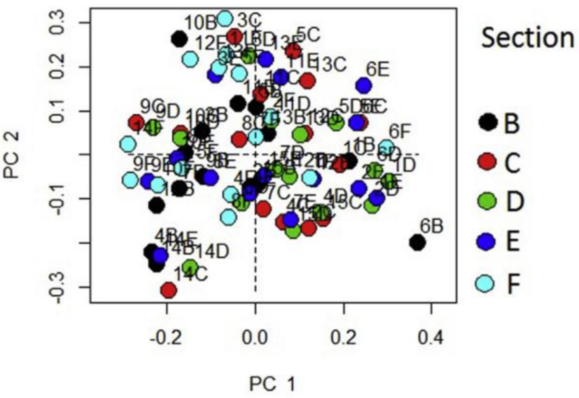

Fig. 11. PCA test of landmark-based morphometrics.

reproduce the results of more costly and difficult-to-access equipment, such as SEM, the new technical 3D digital microscope, or Alicona 3D Infinite Focus Imaging.

In order to define the methodology presented in this article, a wide range of techniques were tested (Table 2). Both methods used by laser techniques (structured lighting and optical triangulation) did not provide the needed resolution. Regarding fotogrametric techniques using parallel photography (Fig. 3a), 3D models looked flat and occationally deformed. The main reason for this problem when using a microscope was its mobility in the cenital axis rather than in the X and Y axes. It implied the need to move the object in those axes in order to photograph it. However, it was not recommended in photogrametry as the object should be kept still and the sensor would move. In the case of using a photographic camera supplemented by specific, the limited distance between the object and the sensor did not favor beams intersection in the 3D reconstruction and reduced the quality of the models. Finally,

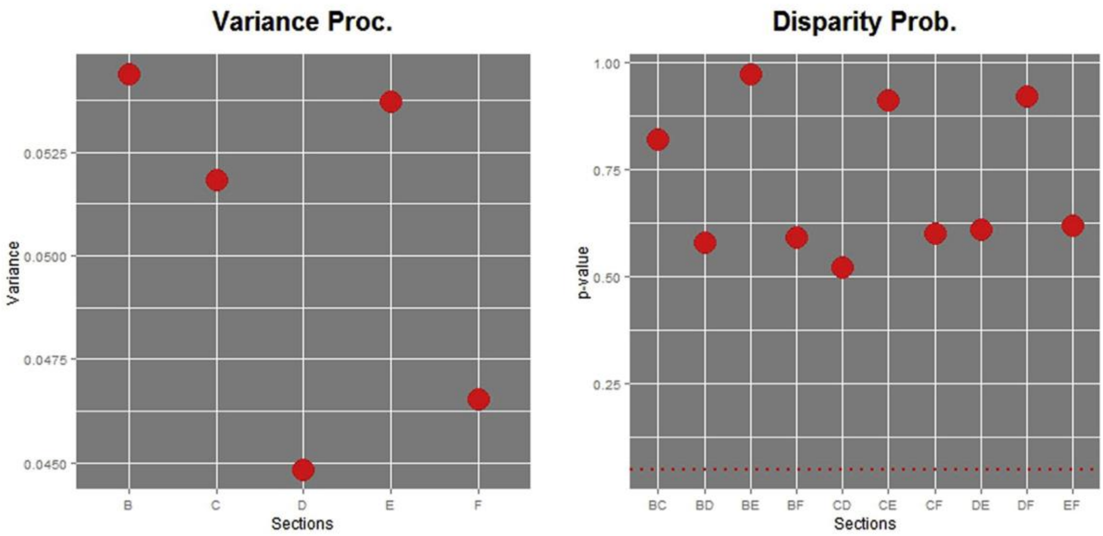

Fig. 12. Results of disparity tests.

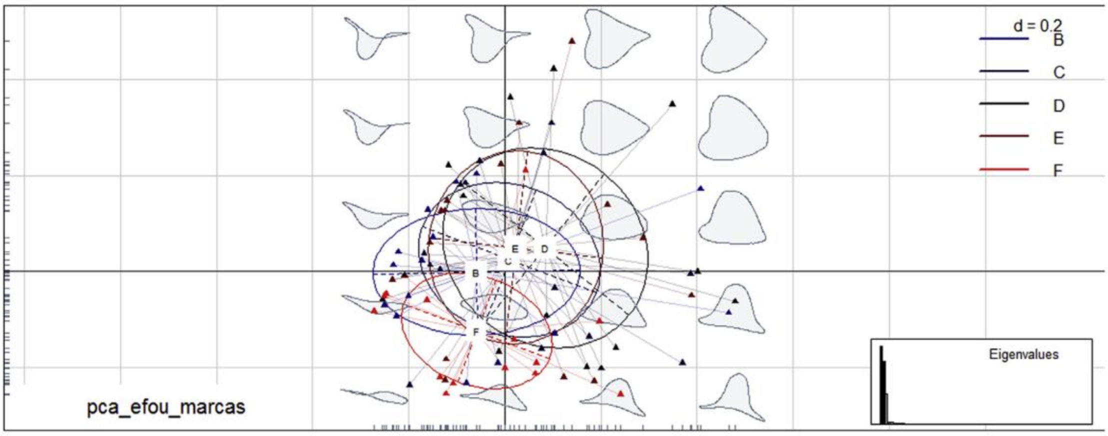

Fig. 13. PCA test of outlines morphometrics.

photogrametric techniques which used oblique photography (Fig. 3b) supplementing the camera with a specific gadget provided a more stable and better system to take the photographs, significantly improving the quality of the images. Hence, the method chosen includes a camera and an additional macro objective.

It may be concluded that it was possible to develop a fast and profitable method that generated high quality (average GSD (mm) = 0.0103; average precision (mm) = ±0.0221) 3D models of cut marks on bones. It was based on improved photogrammetry, together with computer vision techniques and the algorithms and numeric methods which transformed 2D (images) into 3D (point clouds) in an automatic, flexible and high-quality way. In this sense, macro-photogrammetric methodology was better than laser systems, generating higher quality and better resolution 3D models.

In this paper, an alternative method for the study of cut marks by using the in-house tool PW (Photogrammetry Workbench) was explained. The procedure described facilitated a more precise analysis of cut marks and the study of larger samples of bones with cut marks in a short time. The similarities between the values in most sections (30%–70% of the groove) further showed that the location to be studied may be equally efficient, enabling the morphological comparison of marks made with different tool types, raw materials or the age pattern of the different individuals in the future. The preliminary analyses in process seem to indicate differences between the cut marks produced with varying materials, such as the absence of microestriations in the cut marks produced with metal tools when compared to stone flakes.

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References

Abrams, G., Bello, S.M., Di Modica, K., Pirson, S., Bonjean, D., 2014. When Neanderthals used cave bear (Ursus spelaeus) remains: bone retouchers from unit 5 of Scladina Cave (Belgium). Quat. Int. 326–327, 274–287.

Bartelink, E.J., Wiersema, J.M., Demaree, R.S., 2001. Quantitative analysis of sharp-force trauma: an application of scanning electron microscopy in forensic anthropology. J. Forensic Sci. 46, 1288–1293.

Behrensmeyer, A.K., Gordon, K.D., Yanagi, G.T., 1986. Trampling as a cause of bone surface damage and pseudo-cutmarks. Nature 319, 768–771.

Bello, S.M., 2011. New results from the examination of Cut-Marks using three-dimensional imaging. In: Ashton, N., Lewis, S.G., Stringer, C. (Eds.), The Ancient Human Occupation of Britain, Amsterdam: The Netherlands, pp. 249–262.

Bello, S.M., Soligo, C., 2008. A new method for the quantitative analysis of cutmark micromorphology. J. Archaeol. Sci. 35, 1542–1552.

Bello, S.M., Parfitt, S.A., Stringer, C.B., 2009. Quantitative micromorphological analyses of cut marks produced by ancient and modern handaxes. J. Archaeol. Sci. 36, 1869–1880.

Bello, S.M., Parfitt, S.A., Stringer, C.B., 2011a. Earliest directly-dated human skull-cups. PLoS One 6 (2), e17026. http://dx.doi.org/10.1371/journal.pone.0017026.

Bello, S.M., Verveniotou, E., Cornish, L., Parfitt, S.A., 2011b. Dimensional microscope analysis of bone and tooth surface modifications: comparisons of fossil specimens and replicas. Scanning 33, 316–324.

Bello, S.M., De Groote, I., Delbarre, G., 2013a. 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.

Bello, S.M., Parfitt, S.A., Groote, I., Kennaway, G., 2013b. Investigating experimental knapping damage on an antler hammer: a pilot-study using high-resolution imaging and analytical techniques. J. Archaeol. Sci. 40, 4528–4537.

Bello, S.M., Saladié, P., Cáceres, I., Rodríguez-Hidalgo, A., Parfitt, S.A., 2015. Upper Palaeolithic ritualistic cannibalism: Gough's Cave (Somerset, UK) from head to toe. J. Hum. Evol. 82, 170–189.

Binford, L.R., 1981. Bones: Ancient Men, Modern Myths. Academic press, New York.

Bonney, H., 2014. An investigation of the use of discriminant analysis for the classification of blade edge type from cut Marks made by metal and bamboo blades. Am. J. Phys. Anthropol. 154, 575–584.

Boschin, F., Crezzini, J., 2012. Morphometrical analysis on cut marks using a 3D digital microscope. Int. J. Osteoarchaeol. 22, 549–562.

Bunn, H.T., 1982. Meat Eating and Human Evolution: Studies on the Diet and Subsistence Patterns of Plio-pleistocene Hominids in East Africa. Ph.D. dissertation. University of California, Berkeley.

Bunn, H.T., Kroll, E.M., 1986. Systematic butchery by Plio-Pleistocene hominid at 27 olduvai Gorge, Tanzania. Curr. Anthropol. 27, 431–452.

Capaldo, S.D., 1997. Experimental determinations of carcass proceding by Plio-Pleistocene hominids and carnivores at FLK 22 (Zinjanthropus), Olduvai Gorge, Tanzania. J. Hum. Evol. 33, 555–598.

Choi, K., Driwantoro, D., 2007. Shell tool use by early members of Homo erectus in Sangiran, central Java, Indonesia: cut mark evidence. J. Archaeol. Sci. 34, 48–58.

Core, R. Team, 2013. A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL. http://www.R-project.org/.

Crezzini, J., Boschin, F., Wierer, U., Boscato, P., 2014. Wild cats and cut marks: exploitation of *Felis silvestris* in the Mesolithic of Galgenbühel/Dos de la Forca (South Tyrol, Italy). Quat. Int. 330, 52–60.

De Juana, S., Galán, A.B., Domínguez-Rodrigo, M., 2010. Taphonomic identification of cut marks made with lithic handaxes: an experimental study. J. Archaeol. Sci. 37, 1841–1850.

Deseilligny, M.P., Clery, I., 2011. Apero, an open source bundle adjustment software for automatic calibration and orientation of set of images. In: Proceedings of the ISPRS Symposium, 3DARCH11, pp. 269–277.

Domínguez-Rodrigo, M., 1997. Meat eating by early homids at FLK Zinj 22 Site, Olduvay Gorge Tanzania: an experimental a roach using cut-mark data. J. Hum.

Evol. 33, 669–690.
Domínguez-Rodrigo, M., Barba, R., Egeland, C.P., 2007. Deconstructing Olduvai. Springer, New York.
Domínguez-Rodrigo, M., de Juana, S., Galán, A.B., Rodríguez, M., 2009. A new protocol to differentiate trampling marks from butchery cut marks. J. Archaeol. Sci. 36, 2643–2654.
During, E.M., Nilsson, L., 1991. Mechanical surface analysis of bone: a case study of cut marks and enamel hypoplasia on a Neolithic cranium from Sweden. Am. J. Phys. Anthropol. 84, 113–125.
Galán, A.B., Domínguez-Rodrigo, M., 2013. An experimental study of the anatomical distribution of cut marks created by filletng and disarticulation on the long bone ends. Archeometry 55 (6), 1132–1149.
Gilbert, W.H., Richards, G.D., 2000. Digital imaging of bone and tooth modification. Anat. Rec. 261, 237–246.
González-Aguilera, D., Guerrero, D., Hernández-López, D., Rodríguez-Gonzálvez, P., Pierrot, M., Fernández-Hernández, J., 2013. PW, Photogrammetry Workbench. http://www.isprs.org/catcon/catcon6.aspx (accessed 30.04.14).
Greenfield, H.J., 1999. The origins of metallurgy: distinguishing stone from metal cut-marks on bones from archaeological sites. J. Archaeol. Sci. 26, 797–808.
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. J. Field Archaeol. 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 (10), 3105–3114.
Hartley, R., Zisserman, A., 2003. Multiple View Geometry in Computer Vision. Cambridge University Press.
Hillson, S., Parfitt, S.A., Bello, S.M., Roberts, M.B., Stringer, C.B., 2010. Two hominin incisor teeth from the Middle Pleistocene site of Boxgrove, Sussex, England. J. Hum. Evol. 59, 493–503.
Hirschmuller, H., 2005. Accurate and efficient stereo processing by semi-global matching and mutual information. In: IEEE Computer Society Conference on Computer Vision and Pattern Recognition. CVPR 2005, vol. 2, pp. 807–814.
Kaiser, T.M., Katterwe, H., 2001. The application of 3D-Microprofilometry as a tool in the surface diagnosis of fossil and sub-fossil vertebrate hard tissue. An example from the Pliocene Upper Laetoli Beds, Tanzania. Int. J. Osteoarchaeol. 11, 350–356.
Kraus, K., 1993. Photogr. Fundamentals Standard Processes, vol. 1. DummlersVerlag, Bonn, Germany, ISBN 3-427-78684-6.
Lartet, E., 1860. On the coexistence of man with certain extinct quadrupeds, proved by fossil bones from various Pleistocene deposits, bearing incisions made by sharp instruments. Q. J. Sociol. Soc. Lond. 16, 471–479.
Lartet, E., Christy, H., 1875. Reliquiae Acquitanicae Being Contributions to the Archaeology and Paleontology of Perigord and Adjoining Provinces of Southern France. Willians and Nagorte, London.
Lê, S., Josse, J., Husson, F., 2008. FactoMineR: an r package for multivariate analysis. J. Stat. Softw. 25 (1), 1–18.
Lewis, J.E., 2008. Identifying sword marks on bone: criteria for distinguishing between cut marks made by different classes of bladed weapons. J. Archaeol. Sci. 35, 2001–2008.
Longuet-Higgins, H.C., 1987. A computer algorithm for reconstructing a scene from two projections. In: Fischler, M.A., Firschein, O. (Eds.), Readings in Computer Vision: Issues, Problems, Principles, and Paradigms, pp. 61–62.
Lowe, D.G., 1999. Object recognition from local scale-invariant features. In: Proceedings of the 1999 IEEE International Conference on Computer Vision, Kerkyra, Greece, 20–27 September 1999, 2, pp. 1150–1157.
Lyman, R.L., 1987. Archaeofaunas and butchery studies: a taphonomic perspective. In: En Schiffer, M. (Ed.), Advances in Archaeological Method and Theory, vol. 10, pp. 249–337. New York.
Marín-Monfort, M.D., Pesquero, M.D., Fernández-Jalvo, Y., 2014. Compressive marks from gravel substrate on vertebrate remains: a preliminary experimental study. Quat. Int. 330 (30), 118–125.
Martin, H., 1909. Desarticulation des quelques regions chez les rumiants et le cheval a l'epoque mousterienne. Bull. Soc. Préhist. Franç. 7, 303–310.
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 (11), 3349–3353.
Morel, J.M., Yu, G., 2009. Asift: a new framework for fully affine invariant image comparison. SIAM J. Imag. Sci. 2, 438–469.
Nilsen, P.J., 2001. An Actualistic Butchery Study in South Africa and its Implications for Reconstructing Hominid Strategies of Carcass Acquisition and Butchery in the Upper Pleistocene and Plio-pleistocene (Ph.D. dissertation). University of Cape Town.
Olsen, S.L., 1988. The Identification of Stone and Metal Tool Marks on Bone Artefact, vol. 452. BAR, pp. 337–360.
Peale, J., 1870. On the Uses of the Brain and Marrow of Animals Among the Indians of North America. Smithsonian Institution Annual Report for, 1870, pp. 390–391.
Rodríguez-Martin, M., Lagüela, S., González-Aguilera, D., Arias, P., 2015a. Cooling analysis of welded materials for crack detection using infrared thermography. Infrared Phys. Technol. 67, 547–554.
Rodríguez-Martin, M., Lagüela, S., González-Aguilera, D., Arias, P., 2015b. Procedure for quality inspection of welds based on macro-photogrammetric three-dimensional reconstruction. Opt. Laser Technol. 73, 54–62.
Schulting, R.J., Bello, S.M., Chandler, B., Higham, T.F.G., 2015. A cut-marked and fractured Mesolithic human bone from Kent's Cavern, Devon, UK. Int. J. Osteoarchaeol. 25 (1), 31–44.
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., 1981. Life Historia of a Fosil. An Introduction to Taphonomy and Paleoecology. Harvard University Press.
Shipman, P., Rose, J., 1983. Early hominid hunting, buchering and carcass-processing behaviours: a roaches to tha fosil record. J. Anthropol. Archaeol. 2, 57–98.
Smith, M.J., Brickley, M.B., 2004. Animals and interpretation of flint toolmarks found on bones from West Tump Long Barrow, Gloucestershire. Int. J. Osteoarchaeol. 14, 18–33.
Spennerman, D.H.R., 1990. Don't forget the bamboo on recognising and interpretating butchery narcks in tropical faunal assemblages some comments asking for cauting. In: Solomon, S., Davidson, I., Watson, D. (Eds.), Problems Solving Taphonomy Tempus 2, pp. 80–101.
Walker, P.L., 1978. Butchering and stone tool function. Am. Antiq. 43, 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. J. Archaeol. Sci. 34, 512–518.
White, T.E., 1952. Observations on the butchering technique of some aboriginal peoples, 1. Am. Antiq. 17, 337–338.
White, T.E., 1953. Observations on the butchering technique of some aboriginal peoples, 2. Am. Antiq. 19, 160–164.
White, T.E., 1954. Observations on the butchering technique of some aboriginal peoples, 3, 4, 5, 6. Am. Antiq. 19, 254–264.
White, T.E., 1955. Observations on the butchering technique of some aboriginal peoples, 7, 8, 9. Am. Antiq. 21, 170–178.
Yravedra, J., Morín, J., Agustí, E., Sanabria, P., López, M., Urbina, D., López-Frailes, F.J., López, G., Illán, J., 2009. Implicaciones Metalúrgicas de las marcas de corte en la transición Bronce Final-Hierro en el interior de la Península Ibérica.
Zelditch, M.L., Swiderski, D.L., Sheets, H.D., 2012. Geometric Morphometrics for Biologists. Academic Press.

Artículo 2:

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Resumen:

El estudio tafonómico de las marcas de corte sobre hueso ha experimentado un creciente desarrollo en los últimos años. Los análisis tafonómicos de dichas marcas han propiciado grandes avances científicos, como la identificación del consumo de recursos cárnicos en cronologías próximas a 2,5 m.a., el análisis del comportamiento cinegético humano o la discriminación del uso de la metalurgia en el procesado de las carcasas desde el Calcolítico. Entre las técnicas aplicadas al estudio de las marcas de corte, los investigadores se han interesado por encontrar metodologías que sean capaces de diferenciar con qué materias primas o herramientas los *Homo* trataban los recursos cárnicos de su entorno.

Los métodos utilizados tradicionalmente para la realización de estos estudios se basan en las técnicas microscópicas. Estas técnicas presentan buenos resultados pero también algunos problemas (e.g. altos costes, personal especializado, etc.). En el artículo anteriormente presentado (Maté-González et al., 2015), a través de una nueva técnica se han minimizado estos problemas, gracias a la combinación de una metodología multidisciplinar apoyada en técnicas micro-fotogramétricas y en la visión computacional. En este artículo completamos el trabajo mencionado anteriormente presentando el software PANDORA, una herramienta de trabajo que permite estudiar desde perspectivas estadísticas y morfométricas una gran cantidad de variables, agilizando y dinamizando el estudio de marcas de corte en huesos y permitiendo analizar elevadas muestras en poco tiempo.

Con los perfiles de las reconstrucciones 3D de las marcas de corte en hueso obtenidos siguiendo la metodología de Maté-González et al., (2015), se introducen en el software y se seleccionan uno a uno los siete puntos de referencia de cada perfil siguiendo la metodología de Bello et al., (2013).

- <u>Test estadísticos:</u>

El software en cada uno de los perfiles, realiza las siguientes mediciones a partir de los siete puntos de referencia: ancho de la incisión en la superficie (Width of the incision at the surface - WIS), ancho de la incisión en la media (Width of the incision at the mean - WIM), ancho de la incisión en su parte inferior (Width of the incision at its bottom - WIB), ángulo de apertura de la incisión (Opening angle of the incision - OA),

profundidad de la incisión (Depth of the incision - D), profundidad izquierda de la incisión convergente (Left depth of the incision convergent - LDC), profundidad derecha de la incisión convergente (Right depth of the incision convergent - RDC) y ángulo del impacto de la herramienta (Angle of the tool impact - ATI), a partir de las cuales se realizarán los siguientes análisis estadísticos:

- Analysis of variance (ANOVA): Es un análisis de la varianza. Permite determinar si diferentes muestras presentan diferencias significativas o no (Fernández Martínez, 2015).

- Multivariate analysis of variance (MANOVA): Es un análisis multivariante de la varianza. Es una extensión del análisis de la varianza o ANOVA. Sirve para cubrir los casos donde hay varias variables dependientes que no pueden ser combinadas de manera simple. El MANOVA extiende este análisis teniendo en cuenta múltiples variables dependientes continuas, y los agrupa en una combinación lineal ponderada o una variable compuesta. El MANOVA comparará si la combinación recién creada difiere o no por los diferentes grupos o niveles de la variable independiente. De esta manera, el MANOVA esencialmente prueba si la variable de agrupación independiente explica simultáneamente una cantidad estadísticamente significativa de varianza en la variable dependiente (Tabachnick y Fidell, 2012).

  → Dentro del MANOVA está la posibilidad de realizar un PAIRWISE MANOVA en el que se muestra la comparación de las medias de cada grupo por pares. Aquí se puede ver si todos los grupos se diferencian entre sí o no.

  → Tanto el ANOVA como el MANOVA calculan las medias de los grupos que se estén comparando y analiza si estas medias son significativamente distintas o no para comprobar si los grupos se diferencian o no. Si $p < 0.05$ las medias de los grupos son significativamente distintas y, por lo tanto, es posible distinguir entre grupos.

- Principal components analysis (PCA): se trata de un método de estudio en el que las variables son transformadas linealmente y, a partir de cálculos del programa que exploran grandes matrices de datos, se trata de encontrar unas variables "latentes" que no coinciden con las originales observadas pero que explican su variabilidad y correlación (Baxter, 2003; Fernández Martínez, 2015).

- Linear discriminant analysis (LDA): se trata de un modelo basado en un método multivariante que permite discriminar las variables estudiadas en grupos en función de la relación que estas mantienen entre ellas (Baxter, 2003).

  → Crear matrices de confusión por pares o con el grupo completo – jackknife/ one-cross-validation (porcentaje de acierto). Sirve para evaluar los resultados del análisis estadístico y asegurarnos que son independientes los datos de entrenamiento y prueba. Para ello se reiteran los cálculos de la media aritmética obtenida de las medidas de evaluación sobre diferentes particiones hasta encontrar unos valores óptimos totalmente independientes de los datos de entrenamiento.

- <u>Análisis de morfometría geométrica:</u>

- Generalized Procrustes Analysis (GPA): El análisis general de procrustes permite anular los efectos de escala, de traslación y de rotación de las imágenes, para poder comparar directamente la forma de las marcas. Este análisis no hace una comparación entre los diferentes grupos, pero crea la marca "ideal" de cada uno de ellos, al calcular los centroides de los puntos de referencia y los representa gráficamente. También deja preparados los datos normalizados para posteriores análisis estadísticos (Gower, 1975).

  → Siempre quedan algunas diferencias (diferencias Procrustes separadas por distancias Procrustes) que al ser analizadas mediante estadística multivariante exponen patrones de varianza y covarianza entre los elementos analizados.

- PCA y "matriz de distorsión" de los resultados morfométricos: Después del análisis GPA, se puede utilizar una prueba PCA para los datos, que ya está preparada en el paquete "Geomorph" (Adams y Otarola-Castillo, 2013) y que produce un gráfico que expresa la varianza de la muestra.

- LDA en LM: Similar al análisis de PCA, puede hacer un análisis de LDA sobre los resultados de los datos para estudiar la clasificación de grupos usando variables morfológicas.

Para demostrar la utilidad del software, en este artículo se presenta el análisis estadístico y morfométrico de centenares de marcas de corte experimental sobre hueso, realizadas con diferentes materias primas (basalto, sílex y cuarcita). Los resultados demuestran que con los análisis morfométricos es posible identificar correctamente en un elevado número de casos la materia prima con la que se realizaron los cortes.

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Pandora: A new morphometric and statistical software for analysing and distinguishing cut marks on bones

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ABSTRACT

Cut mark studies have experienced a useful development in the last few years. These studies have allowed us to obtain important information about human prehistory spanning from the origin of meat consumption for chronologies around 2.5 Ma, the detection of human hunting behavior during the lower Pleistocene, or even to determine the uses of diverse raw materials on carcases. Amongst the different analyses applied to the study of cut marks, there has been an increasing interest in using morphometry in order to differentiate and characterize the raw materials with which the effectors were made. These techniques have proven to be extremely useful. Nevertheless, this 3D methodology demands the use of expensive equipment and does not allow using an extensive sample, making it a complex and problematic technique. Maté-González et al. (2015) considered an alternative technique, by combining different disciplines involving geometric morphometrics, photogrammetry and multivariate statistics (multidisciplinary methodology). Here, we try to continue with this work presenting *Pandora*, a new open software capable of analysing a useful amount of variables from a statistical and morphometric view, accelerating and simplifying the process.

1. Introduction

Cut marks on bones can provide useful information concerning human behavior. Cut marks have been reported even in sites dated 2.6 Ma, suggesting an early Pleistocene meat consumption by hominins (De Heinzelin et al., 1999; Semaw et al., 2003; Domínguez-Rodrigo et al., 2005). Cut mark frequency and distribution on bones have been used to recognize predatory behaviors for sites dated 1.5 Ma (Domínguez-Rodrigo et al., 2002, 2007, 2009a, 2014; Pickering et al., 2004; Pobiner et al., 2009; Sahnouni et al., 2012). In other chronologies and contexts, cut marks have permitted the identification and use of metal tools in carcass processing from the Chalcolithic to the Bronze Age, showing a functional use of this kind of tools (Greenfield, 1999).

Since the late XIXth century and beginning of the XXth century, cut marks have been observed, documented and studied (Lartet, 1860; Lartet and Christy, 1875; Martin, 1909). Since then, this type of studies have had a large tradition (Walker, 1978; Shipman and Rose, 1983; Olsen, 1988; Spennerman, 1990; Greenfield, 1999, 2004, 2006a, 2006b; Bello and Soligo, 2008; Bello et al., 2009; Domínguez-Rodrigo et al., 2009b; De Juana et al., 2010; Galán and Domínguez-Rodrigo, 2013; Maté-González et al., 2016), and, nowadays, thanks to the development of new technologies, new study types involving the use of complex technology are flourishing, improving the recognition of these marks. This field has progressed greatly, starting with the development of microscopic analysis with SEM used by Shipman (1981), Shipman and Rose (1983), Olsen (1988), and Greenfield (1999, 2004), followed by high resolution binocular microscope pictures used by Domínguez-Rodrigo et al. (2009b) for cut mark morphological characterization through two-dimensional images and, finally, the implementation of three-dimensional reconstruction systems from 3D digital microscopy (Boschin and Crezzini, 2012; Crezzini et al., 2014), such as the 3D Alicona Infinite Focus Imaging microscope (Bello and Soligo, 2008; Bello et al., 2009; Bello, 2011), or even the use of micro-photogrammetric and morphometric reconstruction of cut marks (Maté-González et al., 2015, 2016).

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Although these methods have allowed cut mark characterization, these have some limitations. On one hand some of these techniques are not easily accessible to everybody due to their elevated cost of the expensive equipment (use of SEM or 3D digital microscopes, for instance). On the other hand, using binocular microscopy to obtain high-resolution pictures implies the generation of a 2D image, which does not allow a three dimensional mark characterization. Nevertheless, Maté-González et al. (2015) have introduced the option of carrying out micro-photogrammetric and morphometric reconstructions, developing 3D mark reconstructions using accessible equipment. This new technique allows working with large mark samples (Maté-González et al., 2016) and improves the traditional systems used to analyse these type of marks.

With this paper, we present instructions on the use of the free *Pandora* software. This open access software offers the user a wide variety of tools, such as the application of several statistical and morphometric tests helping to classify and characterize cut marks appearing in archaeological sites. This program allows a great flexibility, automatization and computerization of the data collection process, and can present the data through a large variety of graphs depending on the tests applied.

To demonstrate the technique's results, an experimental case will be carried out throughout this paper as an example of its application to a practical case: the differentiation of cut marks based on the tool's raw material (flint, basalt or quartzite).

2. Methods

2.1. Description and use of the Pandora package

Pandora has been designed to guide the user, step by step, during the data collection and analytical process, simplifying the work required for cut mark microscopic examination. This program has allowed the systematization of all measurements used to classify cut marks, based on the methodology and terminology exposed in Bello et al. (2013) and Maté-González et al. (2015).

Pandora has a series of interactive menus from which the user can make a selection amongst a list of options and configurations, to determine the morphometric and statistical analysis which will be carried out. The main objective of this tool is to obtain a normalized database, allowing different research groups to exchange information and to be able to coordinate studies, synthesizing nomenclature and similar procedures.

Researchers will be able to save their work files in an external file with the extension "*.marks". By doing this, the *Pandora* software would read and process the data and incorporate it into an extensive database, including all other prior data. Because of this, the comparison of cut mark dimensions, characteristics and shapes could be made easier. The successive incorporation of data generated by different experiments and research teams will allow carrying out morphological and statistical tests with a higher resolution and a lower margin of error, since a wider sample will be studied and the data included in it has been collected and analysed following the same methodology during the entire process.

After the three dimensional mark model reflecting the cut mark section has been obtained using photogrammetric methodologies such as those described in Maté-González et al. (2015) or other microscopic techniques like the ones presented in Bello and Soligo (2008), Bello et al. (2009) or Boschin and Crezzini (2012), the images processed should be saved in "*.JPG" format.

Once all the files are located in the same directory, *Pandora* will automatically introduce them to the software database. Automatically, *Pandora* will ask for the specific variables (e.g. "Site", "Raw material", etc.) of each file in the same directory. After this, *Pandora* will once more ask for the specific variables of each of the directory sections, and will ask for image upload. Once the image is open, the program will request to locate scale points with a click to set the image to scale. After that, we should indicate the seven semi-landmarks (LM) used for cut mark analysis as described by Maté-González et al. (2015). Finally, after placing the last LM, *Pandora* will automatically measure all lengths and existent relationships between them and then save them in a database.

When all images in a given folder have been treated and analysed, *Pandora* will give the user two options:

1) To analyse another directory and introduce new data from another set
2) To analyse the introduced images using statistical or morphometric tests

The tests currently included in *Pandora* are ANOVA (Analysis of Variance), MANOVA (Multiple analysis of variance), PCA (Principal Component analysis) and LDA (Linear discriminant analysis) for the statistical tests, and GPA (General Procrustes Analysis), morphometric data PCA and morphometric data LDA referring to the morphometric tests available.

Thus, as soon as the data has been introduced, using several tests, the analysis of a set of cut marks can be done instantaneously. In this case study, we compare the results of various cut marks produced by different raw materials such as flint, quartzite and basalt.

Installing *Pandora* is free, as it is deposited in a repository Github, allowing a quick update whenever necessary and the latest modifications and corrections can always be available and installed (https://www.github.com). *Pandora* uses basic functions of R (Core, 2015), as well as functions of the MASS package (Venables and Ripley, 2002), CircStats (Agostinelli, 2012), and Geomorph (Adams and Otarola-Castillo, 2013).

The use of the *Pandora* package allows a more systematic and automatic data input and manipulation for cut mark analysis, avoiding any errors derived from the manual data input. Before *Pandora* was developed, cut mark analysis implied a series of steps which substantially slowed down the process, as well as implying the use of various different programs such as Autocad, Excel and R for scaling, morphometrical and statistical analysis. Here, all this can be carried out with one single program.

2.2. Methods described in the cut mark analysis

Following the methods developed and proposed by Bello et al. (2013), a series of measurements have been taken, as well as a the three-dimensional model of the cut marks studied. These measurements mentioned above have been used as numerical variables for the analysis of the studied cut marks (Fig. 1).

As it was observed in Maté-González et al. (2015), marks have a variable longitude and the morphology of the mark section changes according to the point chosen to make the three-dimensional model. In this case, we made several statistical analyses to prove which section of the cut mark was diagnostic for cut mark morphology, proving that any point taken in the cut mark between 30% to 70% of the groove section trajectory is equally diagnostic (see Fig. 2).

Measurements, including WIS, WIM, WIB, OA, D, LDC, RDC, were made on the cut mark section (Fig. 1). 7 Landmarks were chosen (LM1x, LM1y, LM2x, LM2y, LM3x, LM3y, LM4x, LM4y, LM5x, LM5y, LM6x, LM6y, LM7x, LM7y), referring to Cartesian coordinates (x and y) of each of the Landmarks (Maté-González et al., 2015, 2016). Next to the qualitative measurements general data such as "site", "n_site", "n", and "Material" has to be added. The definition of all variables is listed below:

1. "site": Original site from where the bones are coming, or the experiment code.
2. "n_site": Name of the bone in the data base of the own project.
3. "n": Mark number.

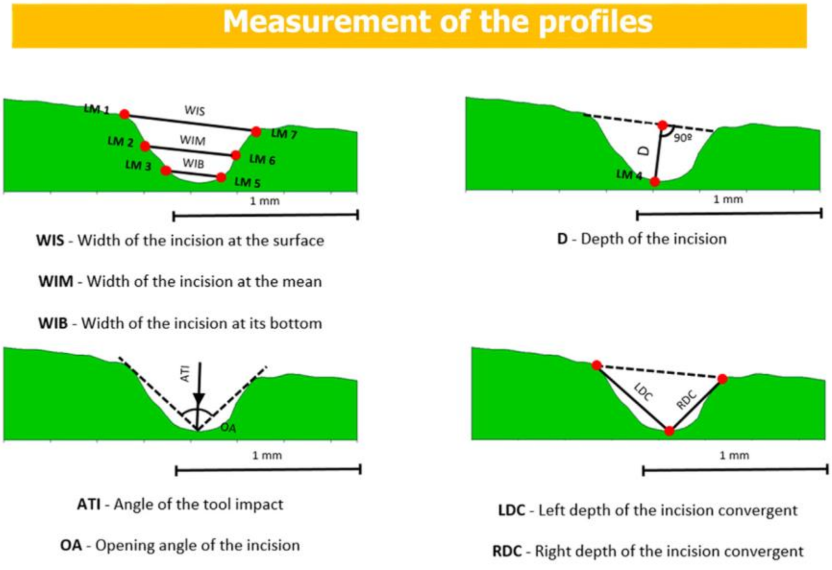

Fig. 1. Location of measurements sensu Bello et al. (2013). Landmarks (LM1–7) used for the morphometric model are also represented.

4. "Material": Edge material producing the mark during the experiment.
5. "Section": Area where has been taken the mark section for the tridimensional model.
6. "taxon_bone": Bone taxa.
7. "Anatomical_part": Skull, mandible, tibia, femur, radius, scapula, pelvis, etc.
8. "WIS": Upper section mark width.
9. "WIM": Middle section mark width.
10. "WIB": Lower section mark width.
11. "LDC": Distance between the mark's base and the upper left point.
12. "RDC": Distance between the mark's base and the upper right point.
13. "SI": Symmetry index (difference between LDC and RDC absolute values).
14. "D": Cut mark depth.
15. "OA": Cut mark angle.
16. "ID": Mark identification code.

All these variables are stored in the database when running the program, in order to be analysed at a later time. The package also allows to export information to an external file to save and share it, and it allows making statistical and morphological tests such as:

Pairwise ANOVA: Variance analysis of each variable separating the marks by raw material and comparing paired groups.

MANOVA: Similar to ANOVA test but uses 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.

PCA: Analysis using the total sample, separating the results by raw material. Whether or not different variable combinations maximize existing differences between different cut mark groups can be studied.

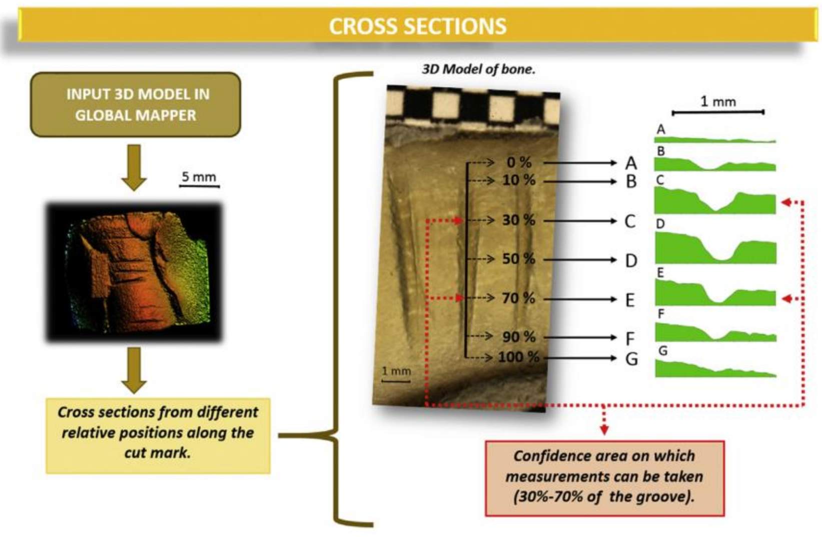

Fig. 2. Representation of the a–g sections of the cut mark regarding its length.

It allows to know if the variables maximize the difference between the different mark groups based on different variable combinations. Results can be shown graphically.

LDA: Lineal discriminant analysis grouping data, showing the degree of similarity between groups and miss classification rates.

GPA: This is the main analysis used for the geometric morphometry. The general procrustes analysis allows nullifying the scale effects as well as image rotation, so it can compare directly the mark shape. This analysis creates the idealized cut mark of each group by calculating the centroids and representing them graphically. Furthermore, since the data is normalized, it is left ready for any future statistical analysis of the overall group.

PCA and "distortion matrix" of the morphometric results: After GPA analysis, a PCA test for the data can be used, which is already prepared in the package "Geomorph" (Adams and Otarola-Castillo, 2013), which produces a graph representing the similarities between different cut marks.

LDA on LM: Similar to PCA analysis, it can make a LDA analysis upon data results to study group classification using morphological variables.

3. *Pandora* practical application to cut mark study

3.1. Materials and methods

After describing *Pandora*, we proceed to present in this chapter its practical applications in a referential framework comparing cut marks produced with different raw materials such as flint, quartzite and basalt.

A total of 198 flint marks, 10 quartzite marks and 85 basalt marks have been analysed, which means a total of 390 marks for the three raw materials. What we would like to achieve with this exercise is to discriminate the cut marks produced by those three materials and see if they can be distinguished using statistical and morphological tests carried out by *Pandora*.

Mark modelling has been made following the methods presented in Maté-González et al. (2015, 2016). This method incorporates the treatment of high-resolution images with micro-photogrammetry and computer vision for the three-dimensional reconstruction of cut mark sections. Following the methodology discussed in 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. Like in previous work, a Canon EOS 700D reflex camera (Table 1) was used, with 60 mm macro lenses, which obtained high resolution and high quality images. The cut mark experimentations were carried out by butchering long bones of young ovicaprids by an expert butcher using simple flint, basalt and fine-grained quartzite flakes.

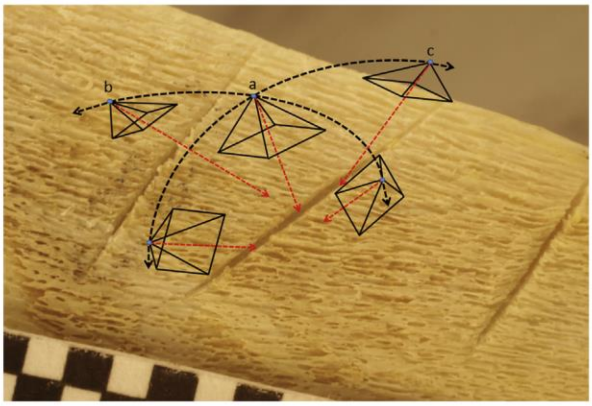

Fig. 3. Protocol for image capture to model a cut mark on a bone by the micro-photogrammetric method, with convergent photographic shots. (a) Master and dependent images in central position, (b) vertical slave images, and (c) horizontal slave images.

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

Marks were subsequently photographed using a tripod to stabilize the camera as described in Maté-González et al. (2015, 2016). In order to homogenize and optimize lighting conditions, the samples were individually placed on a photographic platform adjusting the light to have the bone permanently well exposed to light. Both exposition time and lighting were kept constant during image capture. To produce referenced 3D models, a millimetrical graphic scale was set next to the cut mark. Photographs were then taken following the specified protocol (Fig. 3). Finally, the images were treated with photogrammetric reconstruction software such as GRAPHOS (inteGRAted PHOtogrammetric Suite) (Fig. 4) (González-Aguilera et al., 2016a, 2016b) or another reconstruction software such as Agisoft PhotoScan, PIX4D or PW (González-Aguilera et al., 2013). Once the 3D models with scales were produced, the Global Mapper software was applied to define mark profiles and measure them (Figs. 1 and 2). Finally, the independent analysis of each cut mark was proposed according to the tool used via geometric morphometric analysis. 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 (Fig. 1).

After the modelling of the cut mark sections, every file is saved with the format ".marks", one for each raw material. Right after we proceed to introduce the data and process them by using several statistical tests as described in Section 3. Pairwise ANOVA test for each variable, Pairwise MANOVA test for all variables, and only for statistical significant variables from ANOVA tests, PCA, LDA, GPA, PCA with the statistical results and LDA with the morphometric results.

3.2. Experimental analysis

When carrying out an ANOVA test for each variable measured, carried out for pairs of different raw materials, it is seen that each variable presents a difference in their variance which is statistically significant (5%), for at least two of the raw materials, which means every variable is valid to differentiate between two pieces of different raw materials. That is why, for the next steps those tests will be used.

When MANOVA tests are applied, the following results for p values are obtained:

"F Q" = 7.06482071842748e-28
"B Q" = 6.16912152827254e-21
"B F" = 0.0000482419022222198.

These results present values for p lower than 0.05, meaning statistically significant differences between all the groups studied when this test is applied. Between the raw materials, basalt (B) and flint (F) are the more similar amongst them, with a p value larger than any other combination, but still statistically significant.

When the plot analysis of the PCA is applied (Fig. 5), it can be observed that it is difficult to differentiate between flint and basalt. With a 86.6% of the variance explained in the two observable axis, creating confidence ellipses to 95%, showing that the marks made with quartzite

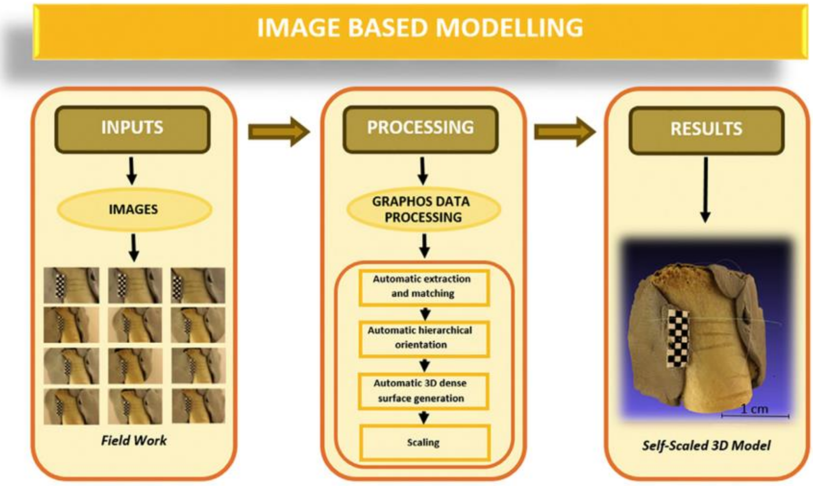

Fig. 4. Image-based modelling technique workflow.

(Q) are clearly separated from the rest. Still, it can be seen that there is an enormous confusion between the marks made with Basalt and Flint, leaving the most part of them overlap with Basalt marks. Employing a LDA we can appreciate it more clearly.

B	F	Q
0.000000	0.994709	0.000000

We can clearly observe that most of the marks made with flint are not distinguishable from other marks.

On the other hand, the morphometric analysis seems more diagnostic than statistical one. The GPA used to normalize and scale coordinates of every Landmark allows us to obtain the centroids of each one (Fig. 6). The data processed, centered and scaled by the GPA is later on analysed with an LDA, which is more decisive to separate cut marks depending on their raw material. As seen on the confusion matrix, we can appreciate differences between the four groups, showing a huge difference between flint and quartzite and between quartzite and basalt. On the other hand, small differences are observed between basalt and flint.

The LDA confusion matrix about morphometric data is:

F	Q	B
0.7460317	0.7102804	0.3882353

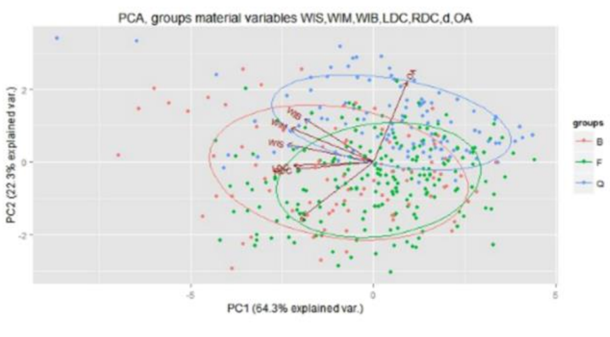

Fig. 5. Flint, basalt y quartzite cut marks PCA.

As flint marks show an enormous variability, if we remove them and remake the LDA just with the basalt and quartzite marks, the resultant confusion matrix is:

Q	B
0.8971963	0.7294118

3.3. Conclusions of the experiment

This experiment allows us to showcase how the *Pandora* software is a useful tool for the analysis of cut marks since after the inclusion of the data it is immediately possible to use an important number of tests automatically. In addition, it is possible to integrate and compare with such analysis different marks produced by as many raw materials as needed. Being capable of analysing different marks from different perspectives, either morphometrically or statistically, the program can simultaneously analyse ample samples improving our limitations from initial cut mark studies, which would only cover a reduced amount of the total sample (Olsen, 1988; Greenfield, 1999, 2004, 2006a, 2006b). On the other hand, being able to make a link between different cut marks could be a necessary step to build a future a tapho-library which could help to identify the raw material used for butchering which caused any studied cut mark in any site.

Referring to the analysis carried out for the variables measured comparing the marks produced with basalt, flint and quartzite, it can be observed that every one of them is proven to be significantly different when separated in groups. This is also true when carrying out a MANOVA test with all the variables. In every case there is a statistical significant difference between the different groups, with a p value lower than 0.05, the lowest difference being between basalt and flint. The dimensional PCA is the analysis with the lowest resolution between those materials, which are actually overlapping. Nevertheless, geometric morphometry appears to present the best results. After the LDA, a higher resolution is obtained, being able to distinguish between different cut marks in relation to the raw material being used.

Real-life applications of the techniques carried out in this study can be seen in many recent archaeological cut mark studies. Taphonomical analyses carried out at archaeological sites such as BK and FLK-W in Bed II at Olduvai Gorge (Tanzania) are a great example of how the use of the *Pandora* package has enabled the differentiation and characterization of cut marks at both sites. Thanks to this software, cut marks have

J.F. Palomeque-González et al. / Journal of Archaeological Science: Reports 13 (2017) 60–66 65

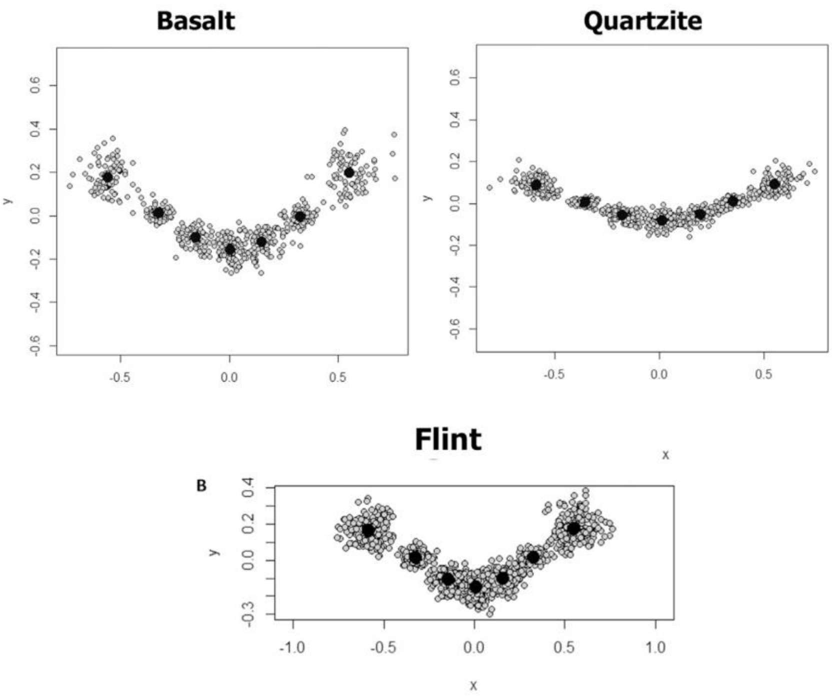

Fig. 6. GPA with each LM centroid.

been inferred to be made with quartzite, not basalt, although both of these raw materials are found at the site (Yravedra et al., 2017a). At FLK-W, faunal remains have been found associated with lithic industry including hand axes (Díez-Marín et al., 2015). By virtue of the use of the *Pandora* software, studies have shown defleshing of the mammal remains was not carried out with said hand axes, but with quartzite chips (Yravedra et al., 2017b).

4. Final considerations

The objective of this paper is to present *Pandora* as a morphometric and statistical analysis tool, which can help to characterize and discriminate cut marks in relation to the raw material used. Even though this study has only been exposed to an experimental analysis comparing marks produced by basalts, flint and quartzite with satisfactory results, the potential of this software is noticeable.

The use of the *Pandora* package implies several advantages: on one hand it is an autonomous system in which the program guides the user during all the process of data acquisition and input; on the other hand, all introduced information is saved globally, allowing the construction of databases which could be used and compared by different research groups. This means studies of cut marks produced with diverse raw materials by different researchers could be contrasted and then be further used to more exhaustively study the archaeological record. Being an autonomous program, it is only necessary to introduce the shape and the Landmarks into the system. Measurements are then calculated by the program automatically, avoiding manual mistakes and saving time. With *Pandora*, when we introduce mark shapes and place Landmarks, all data is kept registered.

Finally, *Pandora*'s intuitive interface and detailed guide have been designed to provide easy use and management, meaning anyone with basic computing skills can use the software. The analytical method presented for *Pandora* complements other powerful three-dimensional microscopic approaches to the study of cut marks. Concerning its application, although our research has been focused on cut mark studies, it could in fact be used to define other marks such as carnivore scores, trampling or even traces made by human beings when producing mobile and parietal art.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jasrep.2017.03.033.

References

Adams, D.C., Otarola-Castillo, E., 2013. Geomorph: an R package for the collection and analysis of geometric morphometric shape data. Methods Ecol. Evol. 4, 393–399.
Agostinelli, 2012. CircStats: Circular Statistics, From "Topics in circular Statistics" (2001).
Bello, S.M., 2011. New results from the examination of cut-marks using three-dimensional imaging. In: Ashton, N., Lewis, S.G., Stringer, C. (Eds.), The Ancient Human Occupation of Britain, pp. 249–262 Amsterdam: The Netherlands.
Bello, S.M., Soligo, C., 2008. A new method for the quantitative analysis of cutmark micromorphology. J. Archaeol. Sci. 35, 1542–1552.
Bello, S.M., Parfitt, S.A., Stringer, C.B., 2009. Quantitative micromorphological analyses of cut marks produced by ancient and modern handaxes. J. Archaeol. Sci. 36, 1869–1880.
Bello, S.M., Parfitt, S.A., Groote, I., Kennaway, G., 2013. Investigating experimental knapping damage on an antler hammer, a pilot-study using high-resolution imaging and analytical techniques. J. Archaeol. Sci. 40, 4528–4537.
Boschin, F., Crezzini, J., 2012. Morphometrical analysis on cut marks using a 3D digital microscope. Int. J. Osteoarchaeol. 22, 549–562.

Core, R. Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria URL. https://www.R-project.org/.
Crezzini, J., Boschin, F., Boscato, P., Wierer, U., 2014. Wild cats and cut marks: exploitation of *Felis silvestris* in the Mesolithic of Galgenbühel/Dos de la Forca (South Tyrol, Italy). Quat. Int. 330, 52–60.
De Heinzelin, J., Clark, J.D., White, T., Hart, W., Renne, P., Wolde Gabriel, G., Beyene, Y., Vrba, E., 1999. Environment and behavior of 2.5–million–year-old Bouri hominids. Science 284, 625–629.
De Juana, S., Galán, A.B., Domínguez-Rodrigo, M., 2010. Taphonomic identification of cut marks made with lithic handaxes, an experimental study. J. Archaeol. Sci. 37, 1841–1850.
Díez-Marín, F., Sánchez Yustos, P., Uribelarrea, D., Baquedano, E., Mark, D.E., Mabulla, A., Fraile, C., Duque, J., Díaz, J., Pérez-González, A., Yravedra, J., Egeland, C.P., Organista, E., Domínguez-Rodrigo, M., 2015. The origin of the Acheulean: the 1.7 million-year-old site of FLK West, Olduvai Gorge (Tanzania). Sci. Rep. Nat. Sci. Rep. 5:17839. http://dx.doi.org/10.1038/srep17839.
Domínguez-Rodrigo, M., de la Torre, I., Luque, L., Alcalá, L., Mora, R., Serrallonga, J., Medina, V., 2002. The ST site complex at Peninj, West Lake Natron, Tanzania: implications for early hominid Behavioural models. J. Archaeol. Sci. 29, 639–665.
Domínguez-Rodrigo, M., Pickering, T.R., Semaw, S., Rogers, M., 2005. Cutmarked bones from archaeological sites at Gona, Afar, Ethiopia: implications for the function of the world's oldest stone tools. J. Hum. Evol. 48, 109–121.
Domínguez-Rodrigo, M., Barba, R., Egeland, C.P., 2007. Deconstructing Olduvai. A Taphonomic Study of the Bed I Sites. Springer Books, Netherland.
Domínguez-Rodrigo, M., Mabulla, A., Bunn, H.T., Barba, R., Diez-Martín, F., Egeland, C.P., Espílez, E., Egeland, A., Yravedra, J., Sánchez, P., 2009a. Unraveling hominin behavior at another anthropogenic site from Olduvai Gorge (Tanzania): new archaeological and taphonomic research at BK, upper bed II. J. Hum. Evol. 57, 260–283.
Domínguez-Rodrigo, M., de Juana, S., Galán, A.B., Rodríguez, M., 2009b. A new protocol to differentiate trampling marks from butchery cut marks. J. Archaeol. Sci. 36, 2643–2654.
Domínguez-Rodrigo, M., Bunn, H.T., Yravedra, J., 2014. A critical re-evaluation of bone surface modification models for inferring fossil hominin and carnivore interactions through a multivariate approach: application to the FLK Zinj archaeofaunal assemblage (Olduvai Gorge, Tanzania). Quat. Int. 322-23, 32–43.
Galán, A.B., Domínguez-Rodrigo, M., 2013. An experimental study of the anatomical distribution of cut marks created by filleting and disarticulation on the long bone ends. Archeometry 55, 1132–1149.
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. J. Archaeol. Sci. 26, 797–808.
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. J. Field Archaeol. 31, 147–163.
Lartet, E., 1860. On the coexistence of man with certain extinct quadrupeds, proved by fossil bones from various Pleistocene deposits, bearing incisions made by sharp instruments. Q. J. Sociol. Soc. Lond. 16, 471–479.
Lartet, E., Christy, H., 1875. Reliquiae Acquitanicae Being Contributions to the Archaeology and Paleontology of Perigord and Adjoining Provinces of Southern France. London Willians and Nagorte, London.
Martin, H., 1909. Desarticulation des quelques regions chez les rumiants et le cheval a l'epoque mousterienne. Bull. Soc. Préhistorique Fr. 7, 303–310.
Maté-González, M.A., Yravedra, J., González-Aguilera, D., Palomeque-González, J.F., Domínguez-Rodrigo, M., 2015. Micro-photogrammetric characterization of cut marks on bones. J. Archaeol. Sci. 62, 128–142.
Maté-González, M.A., Palomeque-González, J.F., 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. Archaeol. Anthropol. Sci. http://dx.doi.org/10.1007/s12520-016-0401-5 (in press).
Olsen, S.L., 1988. The Identification of Stone and Metal Tool Marks on Bone Artefact BAR 452. pp. 337–360.
Pickering, T., Domínguez-Rodrigo, M., Egeland, C.P., Brain, C.K., 2004. New data and ideas on the foraging behavior of early stone age hominids at Swartkrans Cave, South Africa. S. Afr. J. Sci. 100, 215–218.
Pobiner, B.L., Rogersb, M.J., Monahan, C.M., Harrisd, J.W.K., 2009. New evidence for hominine carcass processing strategies at 1.5 Ma, Koobi Fora, Kenya. J. Hum. Evol. 55, 103–130.
Sahnouni, M., Rosell, J., Van der Made, J., Vergès, J.M., Ollé, A., Kandi, N., Harichane, Z., Derradji, Medig, 2012. The first evidence of cut marks and usewear traces from the Plio-Pleistocene locality of El-Kherba (Ain Hanech), Algeria: implications for early hominin subsistence activities circa 1.8 Ma. J. Hum. Evol. 64, 137–150.
Semaw, S., Rogers, M.J., Quade, J., Renee, P.R., Butler, R.F., Stout, D., Domínguez-Rodrigo, M., Hart, W., Pickering, T., Simpson, S.W., 2003. 2.6-million-year-old stone tools and associated bones from OGS-6 and OGS-7, Gona, Afar, Ethiopia. J. Hum. Evol. 45, 169–177.
Shipman, P., 1981. Life Historia of a Fossil. An Introduction to Taphonomy and Paleoecology. Harvard University Press.
Shipman, P., Rose, J., 1983. Early hominid hunting, butchering, and carcass-processing behaviors: approaches to the fossil record. J. Anthropol. Archaeol. 2, 57–98.
Spennerman, D.H.R., 1990. Don't forget the bamboo on recognising and interpretating butchery narcks in tropical faunal assemblages some comments asking for cauting. In: Solomon, S., Davidson, I., Watson, D. (Eds.), Problems Solving Taphonomy Tempus. 2, pp. 80–101.
Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S. fourth ed. Springer, New York.
Walker, P.L., 1978. Butchering and stone tool function. Am. Antiq. 43, 710–715.
Yravedra, J., Maté González, M.A., Palomeque, J.F., Aramendi, J., Estaca-Gómez, V., San Juan Blázquez, M., García-Vargas, E., Organista, E., González-Aguilera, D., Arriaza, M.A., Cobo-Sçanchez, L., Gidna, A., Uribelarrea, D., Baquedano, E., Mabulla, A., Domínguez-Rodrigo, M., 2017a. 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. Boreas http://dx.doi.org/10.1111/bor.12224 (in press).
Yravedra, J., Diez-Martín, F., Egeland, C.P., Maté-González, M.A., Palomeque-González, J.F., Arriaza, M.C., Aramendi, J., García Vargas, E., Estaca-Gómez, V., Sánchez, P., Fraile, C., Duque, J., Francisco-Rodríguez, S.D., González-Aguilera, D., Uribelarrea, D., Mabulla, A., Baquedano, E., Domínguez-Rodrigo, M., 2017b. FLK West (Lower Bed II, Olduvai Gorge, Tanzania): a new early Acheulean site with evidence for human exploitation of fauna. Boreas (Submitted).

Artículo 3:

Título: **Assessment of statistical agreement of three techniques for the study of cut marks: 3D Digital Microscope, Laser Scanning Confocal Microscopy and Micro-Photogrammetry.**

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Resumen:

El estudio de las marcas antropogénicas en las superficies óseas, ha resultado ser fundamental para la interpretación de los yacimientos arqueológicos y para el estudio de las prácticas carniceras prehistóricas. Las marcas de corte en hueso son la evidencia más común del acceso de los *Homo* a los recursos cárnicos.

Las marcas de corte se definen en estudios clásicos, como estrías distintivas en forma de V que aparecen en la superficie de un hueso después de la extracción de la carne en un ser vivo con la ayuda de una herramienta. Su identificación correcta no es fácil, ya que las marcas de corte pueden confundirse con otro tipo de marcas que también aparecen en las superficies óseas (e.g. trampling). En las últimas décadas, se han utilizado muchos criterios para la descripción y la clasificación de las marcas de corte. En este artículo comparamos tres técnicas utilizadas en la reconstrucción virtual y en el análisis de las marcas de corte para evaluar su resolución y sus resultados. Estas técnicas se basan en el uso de dos microscopios (uno digital y otro láser) y de una cámara digital con objetivo macro para crear modelos 3D mediante micro-fotogrametría (Maté-González et al., 2015). En este estudio se han analizado un total de veintiséis marcas de corte experimentales (realizadas con un cuchillo de acero inoxidable), mediante el modelado 3D de estas y la aplicación de la estadística multivalente y una metodología coordinada para la descripción y análisis de la forma. Los resultados demuestran que las tres técnicas utilizadas son igualmente válidas para el estudio de las marcas de corte y, lo que es más importante, que un método no invasivo y de bajo coste como la micro-fotogrametría, es perfectamente válido para la realización de este tipo de análisis.

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Assessment of statistical agreement of three techniques for the study of cut marks: 3D digital microscope, laser scanning confocal microscopy and micro-photogrammetry

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Key words. Experimental cut marks, laser scanning confocal microscopy, micro-photogrammetry, statistical agreement, three-dimensional digital microscope.

Summary

In the last few years, the study of cut marks on bone surfaces has become fundamental for the interpretation of prehistoric butchery practices. Due to the difficulties in the correct identification of cut marks, many criteria for their description and classification have been suggested. Different techniques, such as three-dimensional digital microscope (3D DM), laser scanning confocal microscopy (LSCM) and micro-photogrammetry (M-PG) have been recently applied to the study of cut marks. Although the 3D DM and LSCM microscopic techniques are the most commonly used for the 3D identification of cut marks, M-PG has also proved to be very efficient and a low-cost method. M-PG is a noninvasive technique that allows the study of the cortical surface without any previous preparation of the samples, and that generates high-resolution models. Despite the current application of microscopic and micro-photogrammetric techniques to taphonomy, their reliability has never been tested. In this paper, we compare 3D DM, LSCM and M-PG in order to assess their resolution and results. In this study, we analyse 26 experimental cut marks generated with a metal knife. The quantitative and qualitative information registered is analysed by means of standard multivariate statistics and geometric morphometrics to assess the similarities and differences obtained with the different methodologies.

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Introduction

Taphonomy was first defined as a scientific discipline in the mid-20th century (Efremov, 1940). However, during the 19th century some researchers had already adopted a taphonomic approach. Authors like Knox (1822), Thirria (1833), Tournal (1833), Dawkins & Boyd (1874) or Harlé (1892) observed and analysed bone surface modifications that appeared in Paleolithic deposits. For instance, early examinations of modern captive carnivores led to the conclusion that some old bone accumulations could be the result of the action of carnivores (Thirria, 1833; Tournal, 1833; Dawkins & Boyd, 1874). Cut marks were also investigated as possible evidence of human modification of animal carcasses (Lartet, 1860). In later studies, Lartet & Christy (1875) and Martin (1906, 1907–1910, 1909) investigated the relationship between butchery patterns and cut marks.

Subsequently, during the second half of the 20th century, taphonomy developed integrating a variety of highly specialised methods. One of these methods is based on the study of cut marks. The initial works of Binford (1981), Bunn (1981) and Shipman (1981) laid the foundation of the investigation and current debate on cut marks. Since Martin's (1906, 1907–1910) early studies and during the whole 20th century (White, 1952, 1953, 1954, 1955; Binford, 1981; Bunn, 1981; Shipman, 1981), three independent research lines have been defined for the study of cut marks. The first line of research focuses on the behavioural functionality of the marks according to their location. The activities that led to the creation of the cut marks can be determined based on their anatomical distribution. A specific location of marks corresponds to different activities, such as filleting, disarticulation, evisceration or skinning (see Binford, 1981; Lyman, 1987; Nilsen, 2001; Galán & Domínguez-Rodrigo, 2013, Bello *et al.*, 2016). The second research line focuses on the behavioural meaning of the frequency of marks. The amount of cut marks on any given assemblage varies according to different circumstances (e.g., Domínguez-Rodrigo & Yravedra, 2009). Nevertheless, the combination of frequencies along with the anatomical distribution of marks has been key to discern early access to carcasses by hominins (Domínguez-Rodrigo *et al.*, 2007). Experimental works in this line (Domínguez-Rodrigo, 1997a,b,c; Lupo & O'Connell, 2002) have been useful as reference to differentiate ancient anthropogenic carcass exploitation strategies. The third line of research of cut marks is based on their identification and characterisation. From the 1980s, several experimental studies have attempted to define the characteristics of cut marks and to differentiate them from other types of alterations such as tooth scores or trampling (Martin, 1907–1910; Walker & Long, 1977; Binford, 1981; Shipman, 1981, 1988; Shipman & Rose, 1983; Andrews & Cook, 1985; Behrensmeyer *et al.*, 1986; Olsen & Shipman, 1988; Fiorillo, 1989; Cruz Uribe & Klein 1994; Fisher, 1995; Blasco *et al.*, 2008; Domínguez-Rodrigo *et al.*, 2009, 2010).

Studies focused on the determination of the type of tools or raw materials used to generate cut marks have also become relevant. Notable among these works are those that seek to differentiate cut marks produced with metal knives from those generated by stone tools (Olsen, 1988; Greenfield, 1999, 2004, 2006a,b; Bello & Soligo, 2008; Yravedra *et al.*, 2009), shell (Choi & Driwantoro, 2007), or bamboo (Spennerman, 1990; West & Louys, 2007, Bonney, 2014), or the studies that try to distinguish between lithic tool types including simple or retouched flakes and hand-axes (Walker, 1978; Shipman & Rose, 1983; Bello *et al.*, 2009; Domínguez-Rodrigo *et al.*, 2009; De Juana *et al.*, 2010; Galán & Domínguez-Rodrigo, 2013).

Techniques based on microimages are essential in order to get high-resolution data that allow the identification of the type of tool or raw material used. In these studies, cut mark morphology analyses have been studied using different techniques, such as optic microscopy, hand lenses and scanning electronical microscope (SEM) and environmental scanning electron microscope (ESEM) (Shipman, 1981; Olsen, 1988; Greenfield, 1999, 2004, 2006a,b; Smith & Brickley, 2004; Lewis, 2008; Blasco *et al.*, 2016), binocular microscope for high-resolution pictures (Domínguez-Rodrigo *et al.*, 2009; De Juana *et al.*, 2010; Marín-Monfort *et al.*, 2014), digital imaging techniques (Gilbert & Richards, 2000), three-dimensional (3D) reconstruction (During & Nilsson, 1991; Bartelink *et al.*, 2001; Kaiser and Katterwe, 2001), 3D digital microscope (Boschin & Crezzini, 2012; Crezzini *et al.*, 2014), Alicona 3D Infinite Focus Imaging microscope (Bello & Soligo, 2008; Bello *et al.*, 2009; Bello, 2011; Bonney, 2014), laser scanning confocal microscopy (LSCM) (Archer & Braun, 2013) or micro-photogrammetric techniques (M-PG) (Maté-González *et al.*, 2015, 2016).

All of these techniques have been applied to the analysis of cut marks, but no comparative studies have been conducted to date to test their comparative reliability in the reconstruction of mark section morphology and dimensions. In the present study, we selected a sample of cut marks on different bones and analysed them using 3D DM, LSCM and M-PG in order to assess the resolution of each technique and see if their results are consistent. This has major repercussions for the correct adscription of mark types to agencies and also for the accuracy in identifying cut marks from other types of bone surface modifications.

Method and sample

The sample consists of 26 cut marks, which have been documented using three different techniques: 3D DM, LSCM and M-PG. A total of 78 profiles (three homologous profiles for each cut mark) have been generated in order to create a comparable sample (see below). In all cases, 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. The marks were located on three diaphyses of long bones from a young *Ovis aries* individual (Fig. 1) The age of the individual might be a modifying variable in some cases, but taking into account that the sample used in this study is homogeneous, the age of the prey does not alter the final result.

Cut marks were made with a stainless steel knife model Molybdenum Vanadio C 0.5 CR 14 MO 0.5 VA 0.25 (Fig. 1). The use of a stainless steel knife allows the control of certain variables, because the tool edge characteristics always stay

Fig. 1. Stainless steel knife used in the study to create the cut marks on several bones.

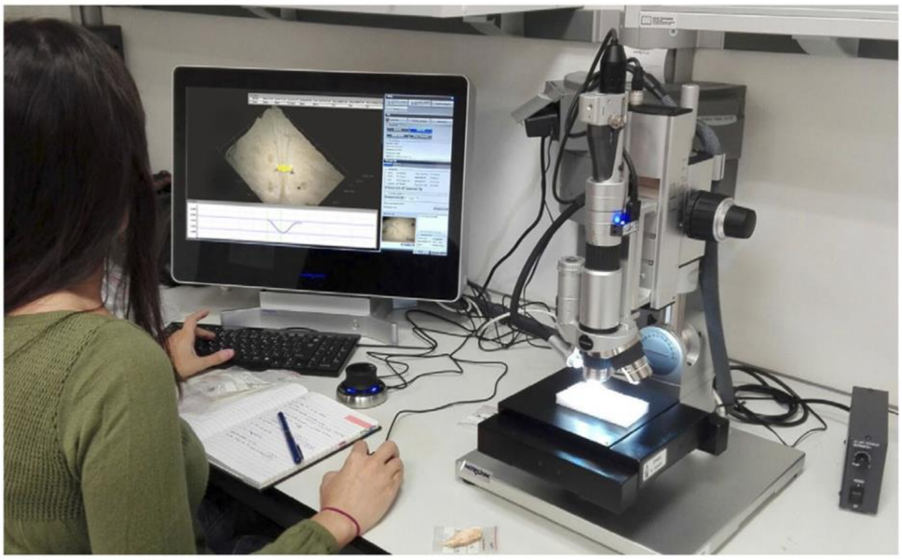

Fig. 2. KH-8700 3D digital microscope in the IPHES, Institut català de Paleoecologia Humana i Evolució Social, Tarragona, Spain.

stable, contrary to other materials such as flint, quartzite or basalt.

All experiments cut marks were made by the same person and the measurements of cut marks of the bones, were made in the same point of cut marks, all techniques analysed the same part of cut mark.

Three-dimensional digital microscope

Cut marks were observed using the KH-8700 3D digital microscope (3D DM) located at IPHES – Catalan Institute of Human Paleoecology and Social Evolution, Tarragona, Spain (Figs. 2 and 3). This microscope uses high-intensity LED optics with a full HD monitor to reconstruct 3D surfaces (Table 1). Its integrated stepping motor allows for an accurate scanning with 0.05 um pulse^{-1} precision and 30 mm of automated travel distance. 3D profiles were generated using a direct overhead light source (LED lamp) and taking a sequence of frames at a specified interval to record changes over the set duration. In our case a total of 25–30 photos were taken for each cut mark. The number of photos was manually determined according to the bone morphology and incision characteristics, such as shape, angle and/or depth. The KH-8700 software allowed us to take images at different elevations and complete the 3D profiles within a temporal range of approximately 20–30 s. The time spent varied according to the number of photos acquired in each case. It is important to note that data collection for cross-sectional profiles depends largely on the intensity and incidence of light. For this reason, it is necessary that the light distribution is uniform on all the area to be scanned. This is sometimes complicated because the depth of some cut marks prevents the light from reaching all points in the same way. The resulting 3D images show a high optical resolution and a wide field of view simultaneously.

Laser scanning confocal microscopy

Cut marks were also recorded using an Olympus LEXT OLS3000 Confocal Laser Microscope (Figs. 4 and 5) at CENIEH – National Research Centre of Human Evolution, Burgos, Spain (Table 2). This microscope is equipped with a 408 nm laser, providing high-resolution images of specific cut mark sections. The motorised stage also provides information from several parameters such as roughness, size and/or shape that is used to generate the 3D reconstructions of transversal sections. The use of the laser allows a real reading of the bone topography, including cut mark transversal morphology, and avoids problems of data collecting derived from the intensity and/or incidence of direct light, such as brightness or shadows. However, the resulting 3D image resolution and quality is not as accurate (including the colour and texture changes) as the one generated by KH-8700 3D Digital Microscope. For data collection, the number of photos was set by default, not exceeding in any case 87 automated steps. Each 3D model and cross-sectional profile for specific points of the cut mark took approximately 40–60 s.

Micro-photogrammetry

Finally, micro-photogrammetry (M-PG) and computer visualisation techniques were used to create high-resolution 3D models of cut mark sections. Precise metrical models were generated using images taken with oblique photography using a CANON EOS 700D (Fig. 6) with a 60 mm macrolens

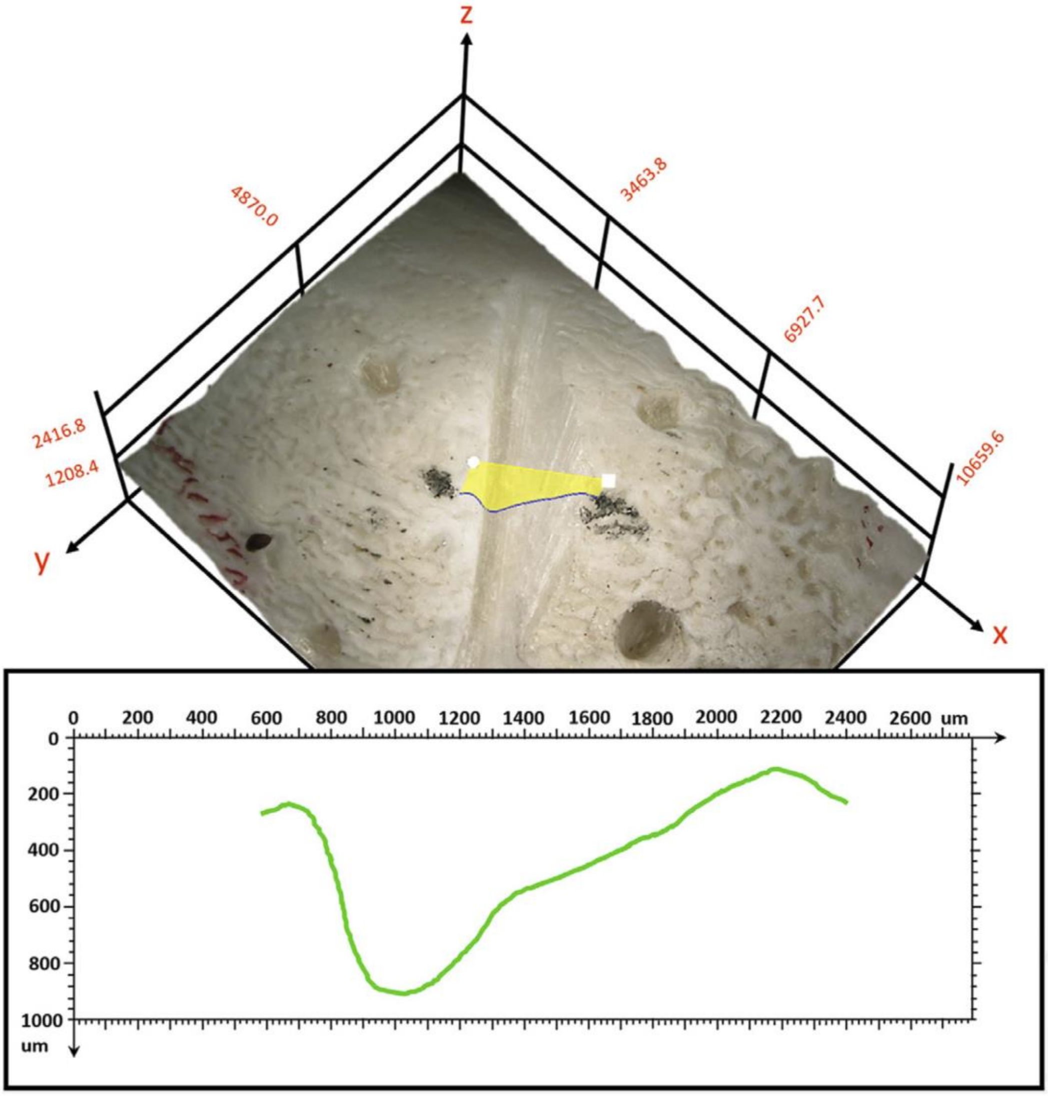

Fig. 3. Data collection and profile generation using the KH-8700 3D digital microscope.

Table 1. Technical specifications of the KH-8700 3D digital microscope.

KH-8700 3D digital microscope	
Type	KH-8700
Sensor size	7.18 × 5.32 mm, 2.11 MP CCD sensor
Pixel size	0.248 (H) × 0.248 (V) mm
Image size	225 MP – 15 000 pixels (H) × 15 000 pixels (V) (tiling image)
Total pixels	2.11 MP 1688 (H) × 1248 (V)
Focal length	10 mm
Focused distance to object	8.71–1.22 mm

(Table 3) and following the specified protocol explained in Maté-González *et al.* (2015). The camera was self-calibrated to simultaneously compute the interior and exterior camera parameters (Fraser, 1980). For data collection, a total of 9–13 photos were 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. Photographs were processed with an open-source photogrammetric reconstruction software GRAPHOS (inteGRAted PHOtogrammetric Suite) (González-Aguilera *et al.*, 2016a,b) to generate a 3D model for each mark. After producing scaled 3D models, Global Mapper software was used to define and measure mark profiles.

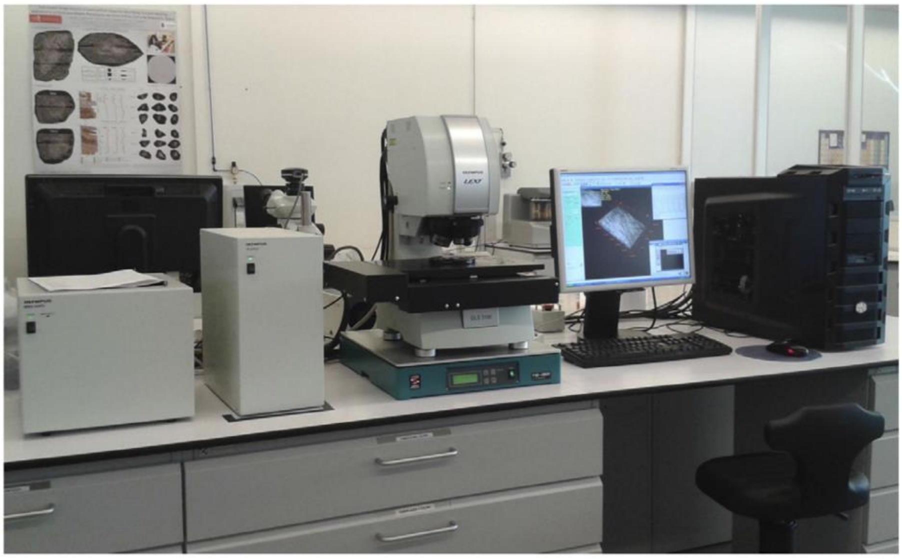

Fig. 4. Olympus LEXT OLS3000 confocal laser microscope in the Microscopy Laboratory of the CENIEH, Centro Nacional de Investigación sobre la Evolución Humana, Burgos, Spain.

Multivariate statistical analysis

A series of measurements (Fig. 7) were taken on each digital model of the mark sections (see Fig. S1). The free software tpsDig2 (v.2.1.7) was used to measure the width of the incision at the surface (WIS), the width of the incision at the mean (WIM), the width of the incision at its bottom (WIB), the opening angle of the incision (OA), the depth of the incision (DB), the left depth of the incision convergent (LDC) and the right depth of the incision convergent (RDC) (*sensu* Bello *et al.*, 2013).

Measurements were imported into the free software R (www.rproject.org, Core-Team, 2015). In order to test if there was any difference in the measurements obtained with each methodology, several statistical tests were performed. First, variance analyses (ANOVA and MANOVA) were applied to statistically assess the presence of separate groups by comparing their means. The Levene's test for homogeneity of variance was included. This test is used to assess equality among two or more sample variances and the feasibility of variance analyses. Second, a multivariate principal components analysis (PCA) of the biometric data was performed. The PCA is a commonly used method for simplification of a large set of variables to few dimensions, and assess patterns of variation among the data. The PCA estimates similarities and differences of marks on a bidimensional Euclidean space and in the present study we used the mark measurements transformed through scaling.

Geometric morphometric analysis

A geometric morphometric analysis was performed as a supplementary alternative to the multivariate metric analysis. In this case, seven homologous points (landmarks) per section – as shown in Figure 7 (LM 1–7) – were considered from each mark. Landmarks were digitalised using tpsUtil (v. 1.60.) and tpsDig2 (v.2.1.7), as explained in Maté-González *et al.* (2015). The location of the landmarks responded to the measures considered for the statistical analysis. LandMark 1 (LM) 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; LM5, LM6 and LM7, in an opposed position to LM3, LM2 and LM1, respectively (Fig. 7). The resulting tps files were edited and imported into MorphoJ (Klingenberg, 2011) to perform the geometric morphometric analysis. MorphoJ is an integrated free software for geometric morphometrics that supports 2D and 3D data. The program was designed for the analysis of biological data, thus it performs better with samples that do vary extremely, as it is the case in this study. MorphoJ geometric morphometric analysis is based on a full Procrusted fit and an orthogonal tangent projection (Dryden & Mardia, 1998) that prepares the sample for usual multivariate statistical analyses.

The seven landmarks digitalised for the whole sample and the three methodologies were first subjected to a general procrustes analysis (GPA). This technique normalises the form information by the application of superimposition procedures. This involves the translation, rotation, and scaling of shapes defined by landmark configurations. After the standardisation of the data, there are always some remaining differences that expose patterns of variation and covariation between structures that after being projected into a flat Euclidian space

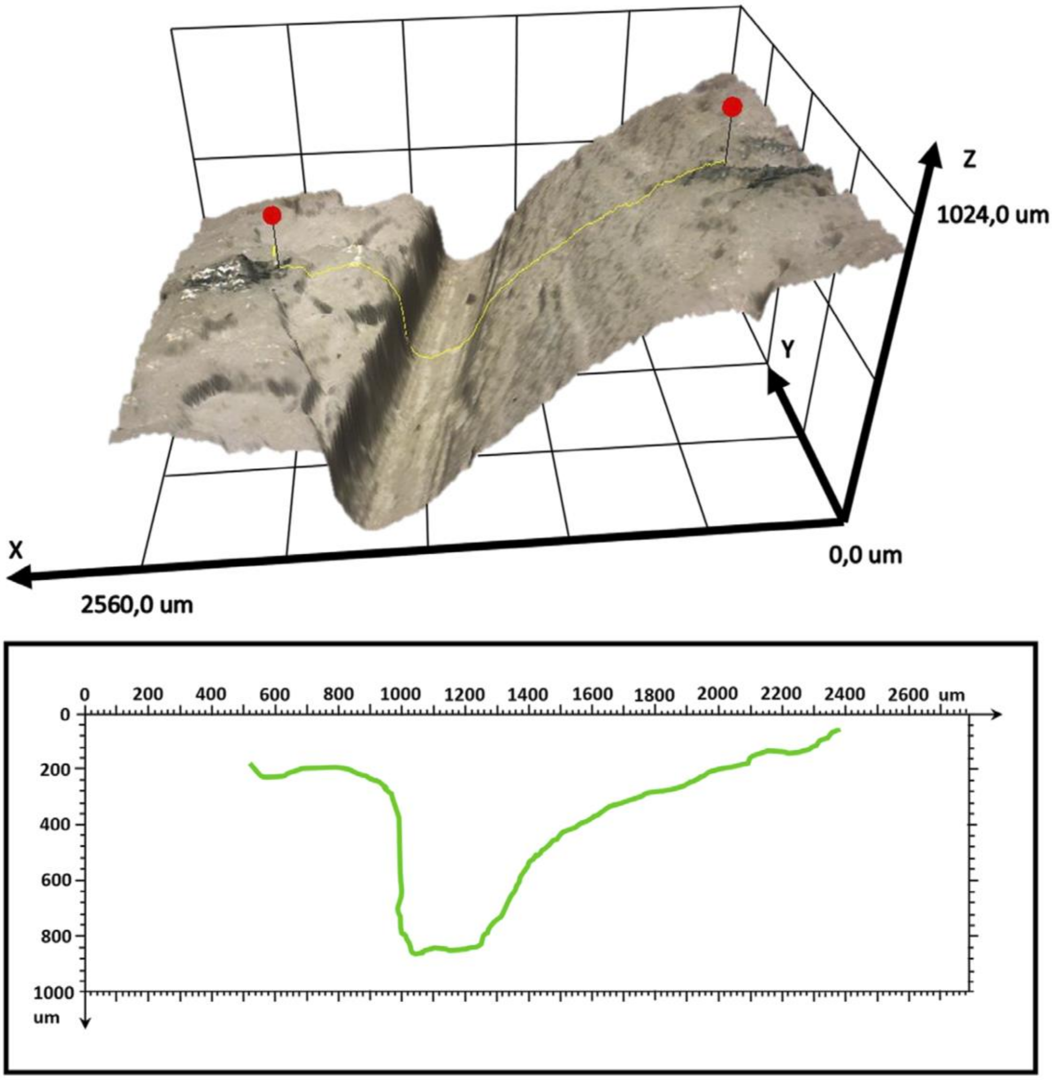

Fig. 5. Data collection and profile generation using the Olympus LEXT OLS3000 confocal laser microscope.

Table 2. Technical specifications of the Olympus LEXT OLS3000 confocal laser microscope.

Olympus LEXT OLS3000 confocal laser microscope	
Type	LEXT OLS3000
	Circle pinhole + photomultiplier
Sensor size	0.12 μm and 0.01 μm Z resolution
Pixel size	12 μm
Image size	1024 × 1024 pixels (for confocal image)
	1024 × 768 pixels (for confocal + colour image)
Total pixels	1 MP (for confocal image)
	0.7 MP (for confocal + colour image)
Focal length	10–45 mm
Focused distance to object	5×–20 mm

can be analysed by means of common multivariate statistics (Slice, 2001; Rohlf, 1999). A PCA in shape space, where only differences in shape excluding size variables are taken into account, was performed for the three samples. PCA scores were later exported and examined for variance: a MANOVA and an ANOVA tests using the Levene's test for equality of variances was performed in R.

Experimental results

The statistical tests applied on all these models show different results, even if the measurements used were always the same (Fig. 7).

The results obtained with MANOVA (Table 4) highlight a significant difference ($p < 0.05$) between the biometric

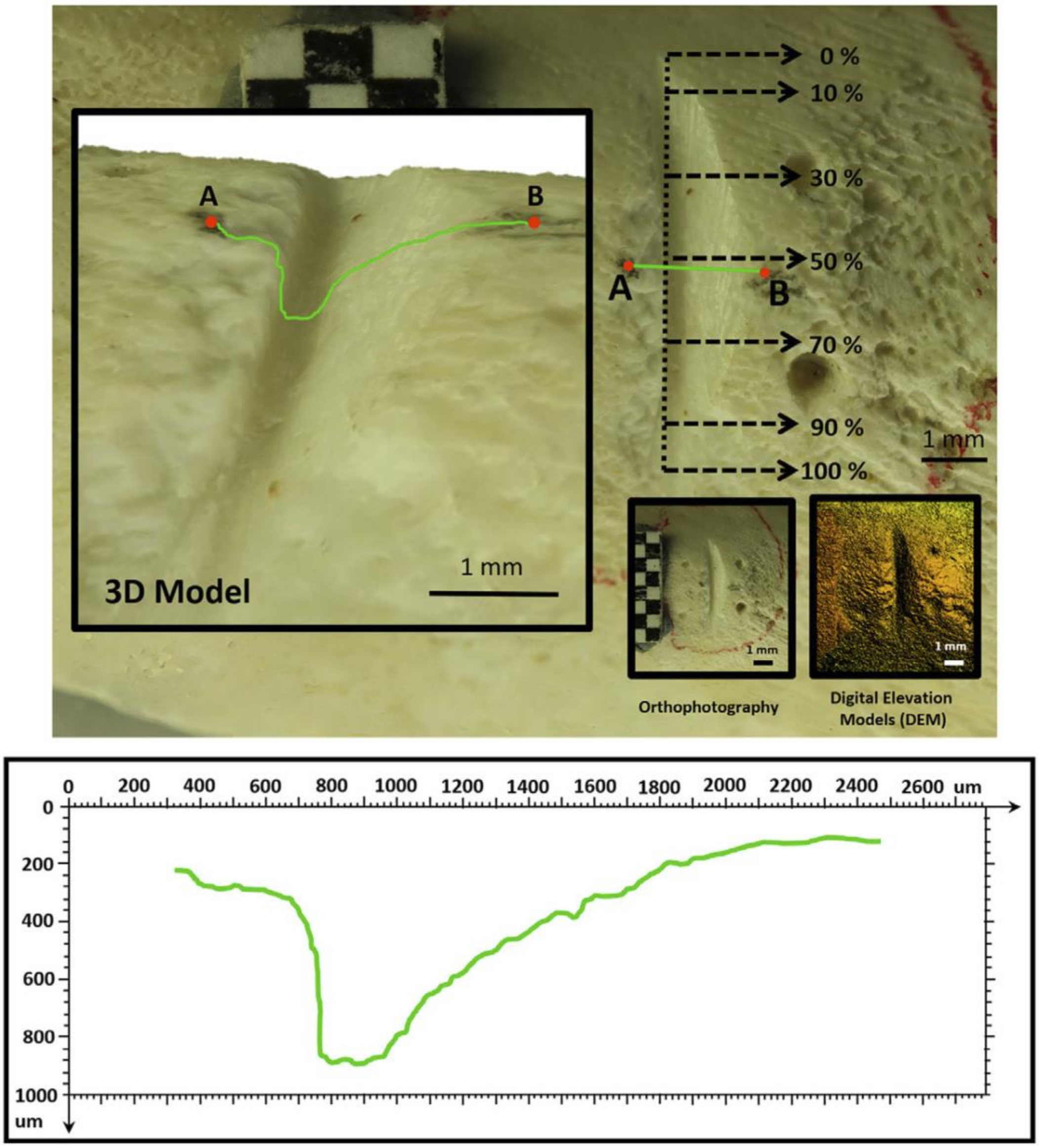

Fig. 6. Data collection and profile generation using micro-photogrammetry.

Table 3. Technical specifications of the photographic sensor with macrolens (Canon EOS 700D).

Canon EOS 700D	
Type	CMOS
Sensor size	22.3 × 14.9 mm
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

measurements obtained with 3D DM and the measurements taken on the models generated by means of M-PG and LSCM, whereas the latter pairwise comparison is similar.

More specifically, when comparing results using single variables at a time the ANOVA (Table 5) and Levene's tests (Table 6) suggest that such differences are not that important. Indeed, the main differences between microscope pairs seem to be focused on the opening angle of the incision (OA) (Tables 5 and 6). The rest of the measurements on the other variables do not allow the distinction between techniques.

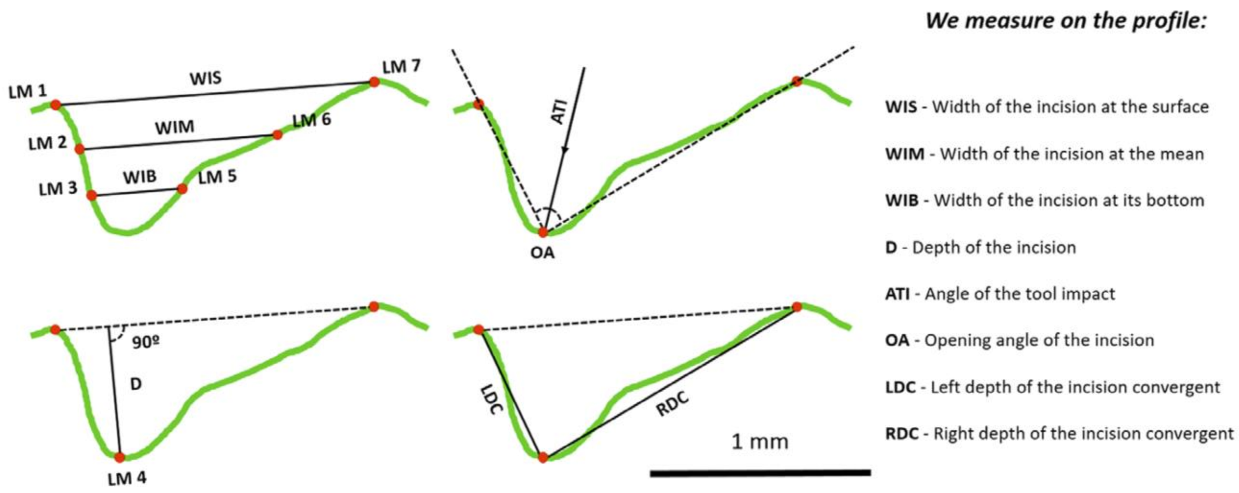

Fig. 7. Location of measurements sensu Bello *et al.* (2013). Landmarks (LM1–7) used for the morphometric model are also represented.

Table 4. Pairwise MANOVA results of the raw metric data.

M-PG – LSCM	0.53008
LSCM – 3D DM	0.030327
3D DM – M-PG	0.0049477

A principal component analysis (PCA) using raw metrics was also performed to compare the cut mark models generated with each technique (Fig. 8). The 95% confidence ellipses of each microscope type overlap with one other, especially those corresponding to the cut marks registered with micro-photogrammetry (Fig. 8, in red) and LSCM (Fig. 8, in green). The cut marks documented with 3D DM (Fig. 8, in black) mostly fall within the space described by the other two methods, but are located in the upper part of the second component. The cut marks are mostly explained by the first two Principal Components (PCs – 85.8% of the total variance). Although PC1 (63.9%) seems to be determined by

Table 5. ANOVA results using single variables of the raw metric data.

	3D DM vs. M-PG vs. LSCM		3D DM vs. LSCM		3D DM vs. M-PG		M-PG vs. LSCM	
	F	*p* Value	*F*	*p* Value	*F*	*p* Value	*F*	*p* Value
WIS	1.882	0.159	2.912	0.094	2.749	0.104	0.008	0.929
WIM	1.436	0.244	1.879	0.177	2.345	0.132	0.021	0.886
WIB	1.794	0.173	0.489	0.488	3.611	0.063	1.450	0.234
D	0.840	0.436	1.263	0.266	1.228	0.273	0.004	0.949
LDC	0.044	0.957	0.035	0.853	0.011	0.915	0.078	0.781
RDC	0.080	0.924	0.151	0.699	0.052	0.820	0.030	0.864
OA	7.457	0.001	11.520	0.001	7.952	0.007	0.244	0.624

Table 6. Results of Levene's test for equality of variance using single variables of the raw metric data.

	3D DM vs. M-PG vs. LSCM		3D DM vs. LSCM		3D DM vs. M-PG		M-PG vs. LSCM	
	Levene's test	*p* Value	Levene's test	*p* Value	Levene's test	*p* Value	Levene's test	*p* Value
WIS	0.110	0.896	0.211	0.648	0.051	0.822	0.062	0.805
WIM	0.065	0.938	0.121	0.730	0.025	0.875	0.044	0.835
WIB	0.267	0.767	0.079	0.779	0.162	0.689	0.739	0.394
D	0.139	0.870	0.001	0.979	0.230	0.634	0.194	0.661
LDC	0.445	0.643	0.478	0.493	0.054	0.818	0.700	0.407
RDC	0.043	0.958	0.004	0.950	0.043	0.836	0.089	0.767
OA	2.941	0.059	5.193	0.027	2.228	0.142	0.707	0.405

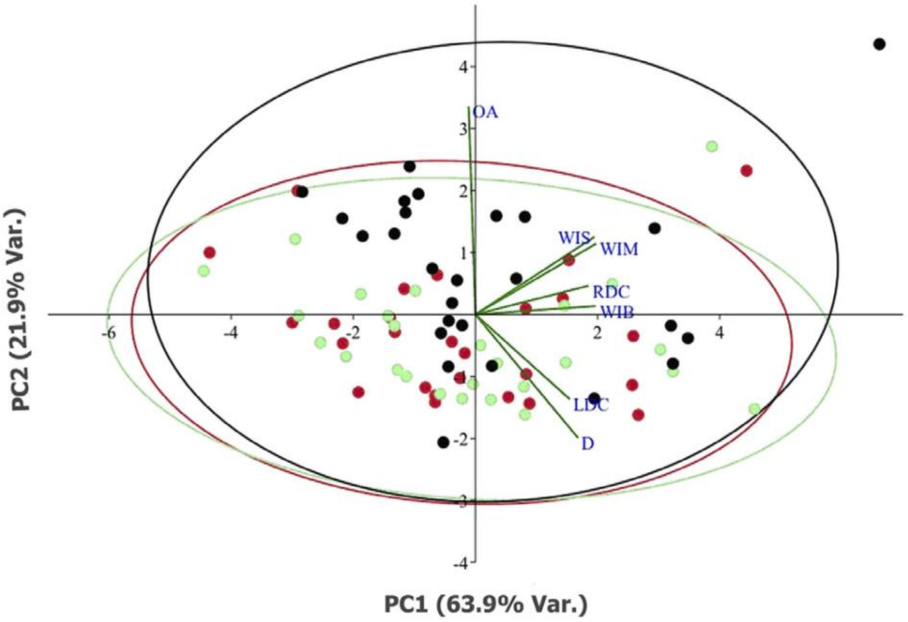

Fig. 8. Principal components analysis (PCA) of the biometric measurements taken on the cut marks models generated using micro-photogrammetric methods (red), LSCM (green) and 3D DM (black).

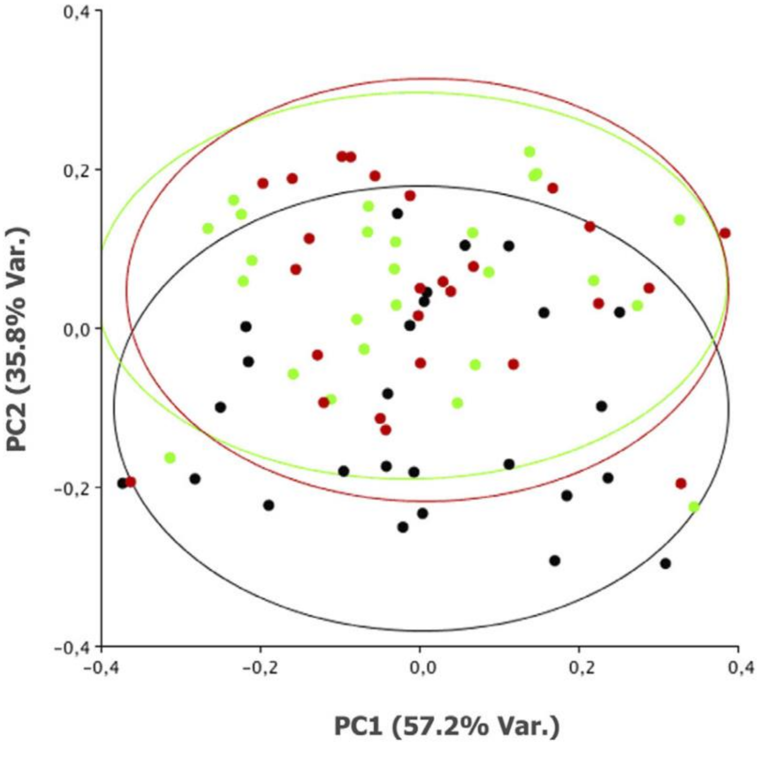

Fig. 9. Morphometric principal components analysis (PCA) after standardisation by means of GPA. Groups corresponding to the different techniques are highlighted in colours: M-PG (red), LSCM (green) and 3D DM (black).

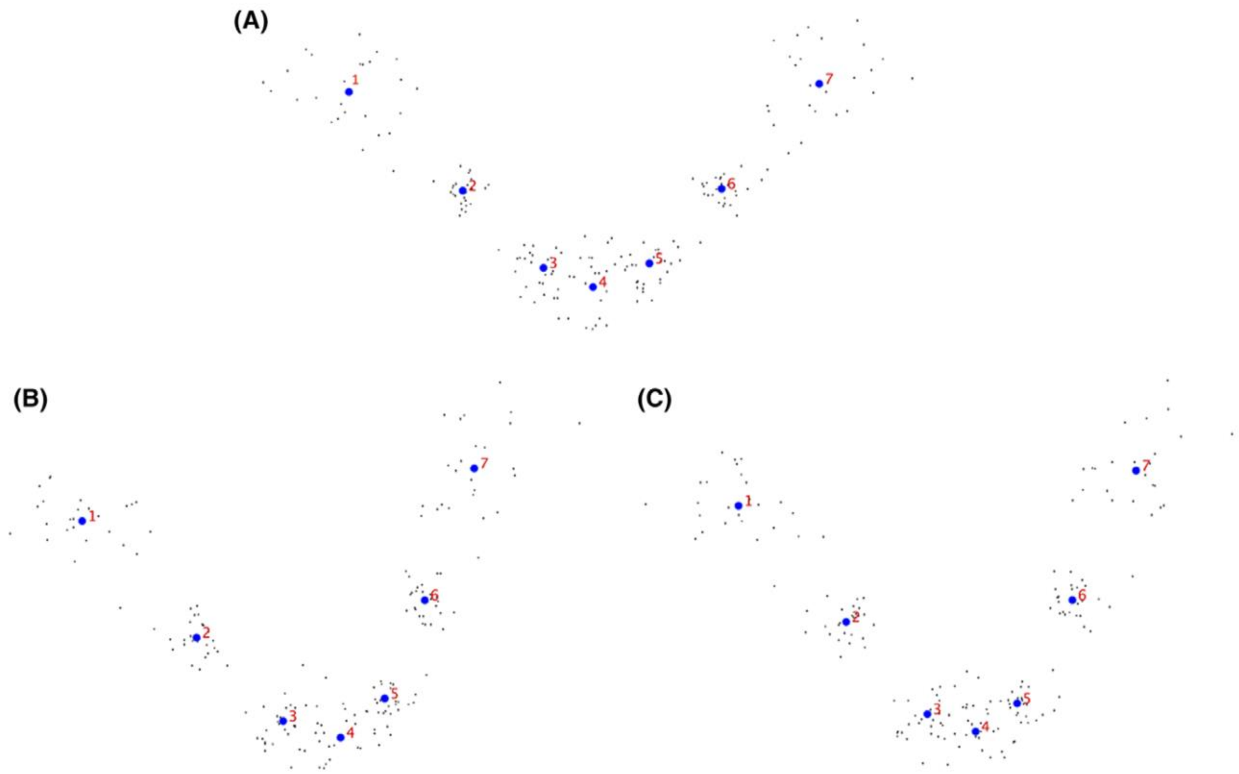

Fig. 10. Silhouettes of cut marks using (A) 3D DM, (B) LSCM and (C) M-PG. The blue points are the centroids associated to each landmark

Table 7. Pairwise MANOVA results of the morphometric data.

M-PG – LSCM	0.72165
LSCM – 3D DM	0.00059659
3D DM – M-PG	0.0030465

the action of most measurements (especially by the width of the incision at its bottom – WIB), PC2 (21.9%) is mostly explained by the opening angle of the incision (OA). Despite the similarities, it is possible to observe a trend towards larger measurements in the cut marks registered with 3D DM.

The geometric morphometric bidimensional analysis of the seven landmarks supports the biometric results. After the GPA, a PCA was conducted (Fig. 9). The three groups of cut marks overlap considerably in the PCA plot where 92.98% of the total variance is explained. However, a slight difference can be noticed, as cut mark models generated using 3D DM show larger values than the other two groups. Marks generated with the electronic microscope are wider and shallower than those generated using the LSCM and M-PG techniques (Fig. 10).

Variance analyses (MANOVA, ANOVA and Levene's test) conducted on the PC scores, support the results obtained with the raw metric data. Although the MANOVA (Table 7) shows a significant difference between 3D DM and the other two techniques, the ANOVA ($F = 0.8782$, $p = 0.453$) and the Levene's test for homogeneity of variance ($p = 0.08126$) do not allow the rejection of the null hypothesis for equal means. However, the Levene's test is closer to the 5% significance level.

Discussion

The present analysis compares three different techniques recently used for the study of taphonomic marks (namely, cut marks) on cortical surfaces. We have observed that the three methods present similar results and are, thus, equally valid for taphonomic metric and morphometric analyses. Although Pante *et al.* (2017) qualified the M-PG method as more inaccurate and prone to error, this prejudiced statement was not supported by any data. Here we show that M-PG meets the standards of more costly and technologically more sophisticated techniques, such as the use of LSCM, and M-PG may even exceed the quality of the results obtained via 3D DM.

The results obtained using the KH-8700 3D Digital Microscope differ slightly (especially in some measurements) from those using the Olympus LEXT OLS3000 Confocal Laser Microscope and the CANON EOS 700D-based M-PG techniques. Differences could be due to the different level of detail

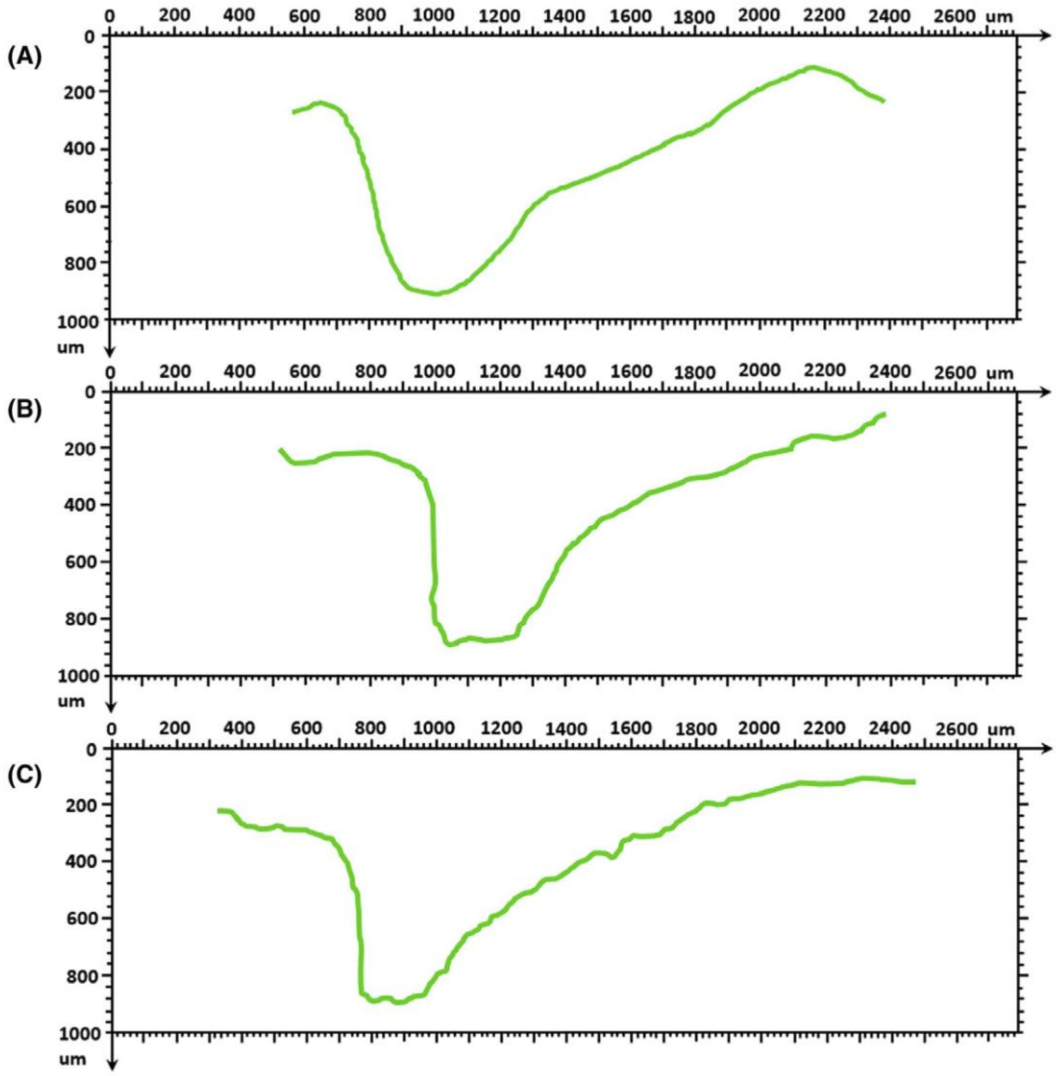

Fig. 11. Homologous profiles of the same cut mark generated with (A) 3D DM3D DM, (B) LSCM and (C) M-PG, where the different level of detail generated by each method can be appreciated.

generated by each method. Although M-PG and LSCM produce high-resolution and very detailed profiles, 3D DM provides less detail. In fact, the ground sample distance (GSD) computed for each technique confirms this aspect: 3D DM-30 μm, LSCM-6 μm and M-PT-7 μm. A less detailed reproduction of the mark profile may vary the location of the landmarks according to their definition (e.g. the end point of the cut mark) as the observer is not able to fully notice the features of the walls that define the limit of the mark (Fig. 11). The lack of details or the major differences in some of the profiles extracted using 3D DM could be due to the data collection process using this kind of microscopes (see differences in the mean profile in Fig. 10). The profile images are created taking a sequence of frames depending largely on the intensity and incidence of light. That means that depending on the lighting the image might vary, so it depends on the observer.

Surprisingly, the low-cost M-PG method, based on the use of a digital camera equipped with 60 mm macrolenses and an open-source photogrammetric software, provides a very good resolution (GSD – 7 μm) and the best level of detail among the three techniques (see the profile in Fig. 11). Although the results obtained in this study are very satisfactory and prove the validity of this low-cost method for the study of conspicuous and well defined marks (e.g. cut marks, scores, pits) as demonstrated by Arriaza *et al.* (2017), Maté-González *et al.* (2016) and Yravedra *et al.* (2017), M-PG might not be valid for the study of inconspicuous and vaguely defined marks (e.g. trampling) where the camera may lack enough resolution to capture the subtleties of fine microscopic details.

The time required for the reconstruction of the marks is short with the three methods analysed in this study. However, M-PG takes more time (around 25 min) than the other two techniques (few seconds). Time differences do not seem to be of such importance to prioritise the expensive methods. In any case, researchers should bear this aspect in mind before choosing the technique for the virtual reconstruction of marks.

In essence, M-PG is a very useful low-cost method which overcomes the limitations implied in the use of microscopes – that is restricted access due to high costs – by reducing analytical costs and, consequently, enlarging the sample to be tested.

Recent research has shown the advantages of obtaining 3D images for the study of taphonomic marks (Bello, 2011, 2013; Boschin & Crezzini, 2012), Paleolithic engravings (Güth, 2012) or Roman pottery graffiti (Montani *et al.*, 2012). Some authors especially highlight the potential of high-resolution 3D studies for the identification of different taphonomic processes (Pante *et al.*, 2017). Using a confocal profilometry, Pante *et al.* (2017) have distinguished between tooth and cut marks. However, this study, although well-intentioned, presents some problems. First, there is no actual need to use 3D analyses to differentiate cut marks from tooth marks, because these marks are easily distinguishable using 10× magnification lenses (Blumenschine *et al.*, 1996). The study would have been more interesting if this technology would have been applied to differentiate agents using a specific type of mark – for example tooth marks produced by different classes of carnivores – or to determine the raw materials used in the exploitation of carcasses on the basis of cut marks or even more relevant, if cut marks were efficiently differentiated from trampling marks and other marks resulting from sedimentary abrasion. Recent micro-photogrammetric and morphometric analyses have approached agency in the determination of carnivore bone modifications, on the basis of tooth scores on bones (Arriaza *et al.*, 2017; Yravedra *et al.*, 2017), as well as the raw materials used in the processing of carcasses through the morphometric analysis of cut marks (Maté-González *et al.*, 2016; Yravedra *et al.*, 2017).

Recently, Pante *et al.* (2017) argued that the new wave of taphonomic studies based on the 3D reproduction of marks should be based on easily available (e.g. low cost) and replicable methods. Here, we have presented a method that clearly meets both needs. The results presented here prove that 3D DM, LSCM and M-PG are more or less equally effective and therefore comparable. Therefore, it would be possible to conduct integrated taphonomic projects to assess mark variability based on different variables such as animal size (Bello *et al.*, 2013), raw material (Maté-González *et al.*, 2016; Yravedra *et al.*, 2017), or tool type (Galán & Dominguez-Rodrigo, 2013; Yravedra *et al.*, 2017) regardless of the technique. Some studies along this research line are already published (Bello & Soligo, 2008; Bello, 2011; Bello *et al.*, 2013, 2015), and they could establish the foundations of future analyses integrating different works using diverse techniques; for example Alicone 3D (Bello & Soligo, 2008; Bello, 2011; Bello *et al.*, 2013), ESEM (Bello *et al.*, 2015; Blasco *et al.*, 2016) M-PG (Maté-González *et al.*, 2016; Yravedra *et al.*, 2017) and LSCM (Archer & Braun, 2013). Future analyses should also include the 3D morphometric and biometric study of the marks. This tool would be especially useful in the case of tooth pits where the extraction of a bidimensional profile might be ignoring important information.

Conclusions

This study has demonstrated that three of the modern analytical techniques recently used for the study of cut marks produced overall statistically similar results and are equally valid for the study of bone surface modifications. Although some small differences have been observed between 3D DM, LSCM and M-PG, they are not important. Particularly surprising is the high degree of similarity between LSCM and M-PG, showing that both completely unrelated techniques can produce statistically indistinguishable results.

The similarity between these techniques allows the comparison of studies using different approaches or techniques. The different methodologies for the 3D modelling of marks can also benefit from the interaction of these techniques. For example, M-PG is a very fast, cheap and useful technique for the study of conspicuous cut or tooth marks in large samples, but it does not have sufficient resolution to analyse trampling marks. On the contrary, LSCM and 3D DM are not as easy available methods because they are expensive, but allow the study of inconspicuos marks thanks to its higher magnification and resolution level. Certain 3D modelling software types, like Alicona, have also shown their high performance, whereas the application of the Confocal Profilometry is still rather anecdotal and its reliability has not been proved yet by testing similar marks (e.g. cut marks made with different tools or raw materials or trampling marks compared to cut marks). For its part, GRAPHOS is distributed through an open source platform (https://github.com/itos3d/GRAPHOS/releases) for research and educational needs. It should be remarked that, up to date, there is not any open source photogrammetric GUI for the scientific community which encloses the modern pipeline of close-range photogrammetry and computer vision.

The compatibility of the three methods used in this study and the possibility of producing comparable high-resolution 3D models using any of them facilitates the future study of taphonomic bone modifications.

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References

Andrews, P. & Cook, J. (1985) Natural modifications to bones in a temperate setting. *Man* **20**, 675–691.

Archer, W. & Braun, D.R. (2013) Investigating the signature of aquatic resource use within Pleistocene hominin dietary adaptations. *PloS One* **8**(8), e69899.

Arriaza, M.C., Yravedra, J., Domínguez-Rodrigo, M. *et al.* (2017) On applications of micro-photogrammetry and geometric morphometrics to studies of tooth mark morphology: The modern Olduvai Carnivore Site (Tanzania). Palaeogeography, Palaeoclimatology, Palaeoecology. doi: 10.1016/j.palaeo.2017.01.036.

Bartelink, E.J., Wiersema, J.M. & Demaree, R.S. (2001) Quantitative analysis of sharp-force trauma: an application of scanning electron microscopy in forensic anthropology. *J. Foren. Sci.* **46**, 1288–1293.

Behrensmeyer, A.K., Gordon, K.D. & Yanagi, G.T. (1986) Trampling as a cause of bone surface damage and pseudo-cutmarks. *Nature* **319**, 768–771.

Bello, S.M. (2011) New results from the examination of cut-marks using three-dimensional imaging. *The Ancient Human Occupation of Britain* (ed. by N. Ashton, S.G. Lewis & C. Stringer), pp. 249–262. Elsevier, Amsterdam, the Netherlands.

Bello, S.M. & Soligo, C. (2008) A new method for the quantitative analysis of cutmark micromorphology. *J. Archaeol. Sci.* **35**, 1542–1552.

Bello, S.M., Parfitt, S.A. & Stringer, C.B. (2009) Quantitative micromorphological analyses of cut marks produced by ancient and modern handaxes. *J. Archaeol. Sci.* **36**, 1869–1880.

Bello, S.M., 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.

Bello, S.M., Saladié, P., Cáceres, I., Rodríguez-Hidalgo, A. & Parfitt, S.A. (2015) Upper Palaeolithic ritualistic cannibalism at Gough's Cave (Somerset, UK): the human remains from head to toe. *J. Human Evol.* **82**, 170–189.

Bello, S.M., Wallduck, R., Dimitrijević, V., Živaljević, I. & Stringer, C.B. (2016) Cannibalism versus funerary defleshing and disarticulation after a period of decay: comparisons of bone modifications from four prehistoric sites. *Am. J. Phys. Anthropol.* **161**(4), 722–743.

Binford, L.R. (1981) *Bones: Ancient Men, Modern Myths*. Academic Press, New York.

Blasco, R., Rosell, J., Férnandez Peris, J., Cáceres, I. & María Vergès, J. (2008) A new element of trampling: an experimental application on the level XII faunalrecord of Bolomor Cave (Valencia, Spain). *J. Archaeol. Sci.* **35**, 1605–1618.

Blasco, R., Rosell, J., Smith, K.T., Maul, L.C., Sañudo, P., Barkai, R. & Gopher, A. (2016) Tortoises as a dietary supplement: a view from the Middle Pleistocene site of Qesem Cave, Israel. *Quarter. Sci. Rev.* **133**, 165–182.

Blumenschine, R.J., Cavallo, J.A. & Capaldo, S.D. (1996) Meat eating, hominid sociality, and home bases revisited. *Curr. Anthropol.* **37**(2).

Bonney, H. (2014) An Investigation of the use of discriminant analysis for the classification of blade edge type from cut marks made by metal and bamboo blades. *Am. J. Phys. Anthropol.* **154**, 575–584.

Boschin, F. & Crezzini, J. (2012) Morphometrical analysis on cut marks using a 3D digital microscope. *Int. J. Osteoarchaeol.* **22**, 549–562.

Bunn, H.T. (1981) Archaeological evidence for meat-eating by Plio-Pleistocene hominids from Koobi Fora, Kenya. *Nature* **291**, 574–577.

Choi, K. & Driwantoro, D. (2007) Shell tool use by early members of Homo erectus in Sangiran, central Java, Indonesia: cut mark evidence. *J. Archaeol. Sci.* **34**, 48–58.

Core-Team, R. (2015) *A language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.Rproject.org/.

Crezzini, J., Boschin, F., Boscato, P. & Wierer, U. (2014) Wild cats and cut marks: exploitation of Felis silvestris in the Mesolithic of Galgenbühel/Dos de la Forca (South Tyrol, Italy). *Quarter. Int.* **330**, 52–60.

Cruz Uribe, K. & Klein, R.G. (1994) Chew marks and cut marks on animal bones from the Kastelberg B and Dune field Midden Later Stone Age sites, Western Cape Province, Soyth Africa. *J. Archaeol. Sci.* **21**, 35–49.

Dawkins, W. & Boyd, H. (1874) *Cave Hunting Research of the Evidence of Caves Respecting the Early Inhabitants of Europe Early Man in Britain*. Macmillian & Co., London

De Juana, S., Galán, A.B. & Domínguez-Rodrigo, M. (2010) Taphonomic identification of cut marks made with lithic handaxes: an experimental study. *J. Archaeol. Sci.* **37**, 1841–1850.

Domínguez-Rodrigo, M. (1997a) Meat eating by early homids at FLK Zinj 22 Site, Olduvay Gorge Tanzania: an experimental a roach using cut-mark data". *J. Human Evol.* **33**, 669–690.

Domínguez-Rodrigo, M. (1997b) A Reassesment of the study of cut marcs patterns to infer hominid manipulation of fleshed carcasses at the FLK Zinj 22 Site, Olduvay Gorge Tanzania. *Trabajos de Prehistoria* **54**(2), 29–42.

Domínguez-Rodrigo, M. (1997c) Meat eating and carcass procurement by hominids at the FLK Zinj 22 site Olduvai Gorge Tanzania. A new experimental a roach to the old hunting-versus-scavenging debate. *Lifestyles and Survival Strategies in Pliocene and Pleistocene Hominids* (ed. by H. Ullrich), pp. 89–111. Edition Archaea, Schwelm Germany.

Domínguez-Rodrigo, M., Barba, R. & Egeland, C.P. (2007) Deconstructing Olduvai: *A Taphonomic Study of the Bed I Sites*. Springer Books, the Netherlands.

Domínguez-Rodrigo, M., de Juana, S., Galán, A.B. & Rodríguez, M. (2009) A new protocol to differentiate trampling marks from butchery cut marks. *J. Archaeol. Sci.* **36**, 2643–2654.

Domínguez-Rodrigo, M., Bunn, H.T. & Pockering, T.R. (2010) Configurational approach to identifying the earliest hominin butchers. *Proc. Nat. Acad. Sci.* **107**(49), 20929–20934.

Domínguez-Rodrigo, M. & Yravedra, J. (2009) Why are cut mark frequencies in archaeofaunal assemblages so variable? A multivariate analysis. *J. Archaeol. Sci.* **36**, 884–894.

Dryden, I.L., & Mardia, K.V. (1998) *Statistical Shape Analysis*. Wiley, Chichester.

During, E.M. & Nilsson, L. (1991) Mechanical surface analysis of bone: a case study of cut marks and enamel hypoplasia on a Neolithic cranium from Sweden. *Am. J. Phys. Anthropol.* **84**, 113–125.

Efremov, L.A. (1940) Taphonomy a new branch of Paleontology Pan. *Am. Geol.* **74**(2), 81–93.

Güth, A. (2012) Using 3D scanning in the investigation of Upper Palaeolithic engravings: results of a pilot study. *J. Archaeol. Sci.* **39**(10), 3105–3114.

Fraser, C. (1980) Multiple focal setting self-calibration of close-range metric cameras. *Photogr. Eng. Remote Sens.* **46**, 1161–1171.

Fiorillo, A.R. (1989) An experimental study of trampling: Implications for the fossil record. In *Bone Modification.* (eds. by R. Bonnichsen & M. Sorg), pp. 61–72. Center for the Study of the First Americans, Orono, ME.

Fisher, D.C. (1995) Bone surface modifications in zooarchaeology. *J. Archaeol. Method Theor.* **2**, 7–68.

Galán, A.B. & Domínguez-Rodrigo, M. (2013) An experimental study of the Anatomical distribution of cut marks created by filleting and disarticulation on the long bone ends. *Archeometry* **55**, 1132–1149.

Gilbert, W.H. & Richards, G.D. (2000) Digital imaging of bone and tooth modification. *Anatom. Rec.* **261**, 237–246.

Greenfield, H.J. (1999) The origins of metallurgy: distinguishing stone from metal cut-marks on bones from archaeological sites. *J. Archaeol. Sci.* **26**, 797–808.

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. *J. Field Archaeol.* **31**, 147–163.

González-Aguilera, D., López-Fernández, L., Rodríguez-González, P. *et al.* (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. *et al.* (2016b) InteGRAted PHOtogrammetric Suite, GRAPHOS. Congress: CATCON7-ISPRS. Date: 12 to 19 of July of the year 2016, Prague, Czech Republic.

Harlé, E. (1892) Presentation del os provenient de rapas de Hyenes tachetees. *Bull. Soc. Hist. Nat. Toulouse. T.* **XXVI**. 22–25.

Kaiser, T.M. & Katterwe, H. (2001) The application of 3D-Microprofilometry as a tool in the surface diagnosis of fossil and subfossil vertebrate hard tissue. An example from the Pliocene Upper Laetoli Beds, Tanzania. *Int. J. Osteoarchaeol.* **11**, 350–356.

Klingenberg, H. (2011) MorphoJ: an integrated software package for geometric morphometrics. *Mol. Ecol. Resour.* **11**, 353–357

Knox, H. (1822) *Notice Relevant to the Habits of Hyaena in Southern Africa*, pp. 1–383. Transitions of the Wernerian Natural history Society, Edinburgh.

Lartet, E. (1860) On the coexistence of man with certain extinct quadrupeds, proved by fossil bones from various Pleistocene deposits, bearing incisions made by sharp instruments. *Quart. J. Sociolog.Soc. Lond.* **16**, 471–479.

Lartet, E. & Christy, H. (1875) *Reliquiae Acquitanicae Being Contributions to the Archaeology and Paleontology of Perigord and Adjoining Provinces of Southern France.* London Willians and Nagorte, London.

Lewis, J.E. (2008) Identifying sword marks on bone: criteria for distinguishing between cut marks made by different classes of bladed weapons. *J. Archaeol. Sci.* **35**, 2001–2008.

Lupo, K.D. & O'Connell, J.F. (2002) Cut and tooth mark distributions on large animal bones: ethnoarchaeological data from the Hadza and their implications for current ideas about early human carnivore. *J. Archaeol. Sci.* **29**, 85–109.

Lyman, R.L. (1987) Archaeofaunas and butchery studies: a taphonomic perspective. *Advances in Archaeological Method and Theory* (ed. by M. Schiffer), vol. **10**, pp. 249–337. Springer, New York.

Nilsen, P.J. (2001) An actualistic butchery study in South Africa and its implications for reconstructing hominid strategies of carcass acquisition and butchery in the Upper Pleistocene and Plio-pleistocene. PhD Dissertation, University of Cape Town.

Marín-Monfort, M.D., Pesquero, M.D. & Fernández-Jalvo, Y. (2014) Compressive marks from gravel substrate on vertebrate remains: a preliminary experimental study. *Quarter. Int.* **330**, 118–125.

Maté-González, M.A., Yravedra, J., González-Aguilera, D., Palomeque-González, J.F. & Domínguez-Rodrigo, M. (2015) Micro-photogrammetric characterization of cut marks on bones. *J. Archaeol. Sci.* **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. Archaeol., Anthropol. Sci. **0**, 1–12. DOI 10.1007/s12520-016-0401-5.

Martin, H. (1906) Presentation d'ossement de rene pertante des lesions d'origene humaine et animale. *Bull. Soc. Préhist. Fran.* **3**, 385–397.

Martin, H. (1907–10). Recherches sur l'evolution du Musterien dans le gisement de la Quina (Charente). Vol. Industrie Osseuse. Paris Schleicher Freres.

Martin, H. (1909) Desarticulation des quelques regions chez les rumiants et le cheval a l'epoque mousterienne. *Bull. Soc. Préhist. Fran.* **7**, 303–310.

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**(11), 3349–3353.

Olsen, S.L. (1988). The Identification of Stone and Metal Tool Marks on Bone Artefacts BAR, vol. 452, pp. 337–360. British Archaeological Reports, Oxford.

Olsen, S.L. & Shipman, P. (1988) Surface modification on bone: trampling vs butchery. *J. Archaeol. Sci.* **15**, 535–553.

Pante, M.C., Muttart, M.V., Keevil, T.L., Blumenschine, R.J., Njau, J.K. & Merritt, S.R. (2017) A new high-resolution 3-D quantitative method for identifying bone surface modifications with implications for the Early Stone Age archaeological record. *J. Human Evol.* **102**, 1–11.

Rohlf, F.J. (1999) Shape statistics: procrustes superimpositions and tangent spaces. *J. Classific.* **16**, 197–223.

Shipman, P. (1981) Life historia of a fosil. *An Introduction to Taphonomy and Paleoecology*. Harvard University Press.

Shipman, P. (1988) Actualistic studies of animal and hominid activities. *The Identification of Stone and Metal Tool Marks on Bone Artifacs BAR* (ed. by S.L. Olsen), vol. **452**, pp. 261–285, 337–360. British Archaeological Reports, Oxford.

Shipman, P. & Rose, J. (1983) Early hominid hunting, butchering and carcass-processing behaviours: a roaches to the fossil record. *J. Anthropol. Archaeol.* **2**, 57–98.

Slice, D.E. (2001) Landmark coordinates aligned by procrustes analysis do not lie in kendall's shape space. *Syst. Biol.* **50**(1), 141–149.

Smith, M.J. & Brickley, M.B. (2004) Animals and interpretation of flint toolmarks found on bones from West Tump Long Barrow, Gloucestershire. *Int. J. Osteoarchaeol.* **14**, 18–33.

Spennerman, D.H.R. (1990) Don't forget the bamboo on recognising and interpretating butchery narcks in tropical faunal assemblages some comments asking for cauting. *Problems Solving Taphonomy Tempus* (ed. by S. Solomon, I. Davidson & D. Watson), vol. **2**, pp. 80–101. Tempus.

Thirria, E. (1833) Statique minéralogique et géologie du département de la Haute-Loire Besançon Outhenin Chalande.

Tournal, M. (1833) General considerations on the phenomenon of bone averns. *Ann. Himie Phys.* **25**, 161–171

Walker, P.L. (1978) Butchering and stone tool function. *Am. Antiq.* **43**(4), 710–715.

Walker, P.L. & Long, L.C. (1977) An experimental study of the morphological characterics of tool marks.*Am. Antiq.* **42**, 605–616.

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. *J. Archaeol. Sci.* **34**, 512–518.

White, T.E. (1952) Observations on the butchering technique of some aboriginal peoples, 1. *Am. Antiq.* **17**, 337–338.

White, T.E. (1953) Observations on the butchering technique of some aboriginal peoples, 2. *Am. Antiq.* **19**, 160–164.

White, T.E. (1954) Observations on the butchering technique of some aboriginal peoples, 3, 4, 5, 6. *Am. Antiq.* **19**, 254–264.

White, T.E. (1955) Observations on the butchering technique of some aboriginal peoples, 7, 8, 9. *Am. Antiq.* **21**, 170–178.

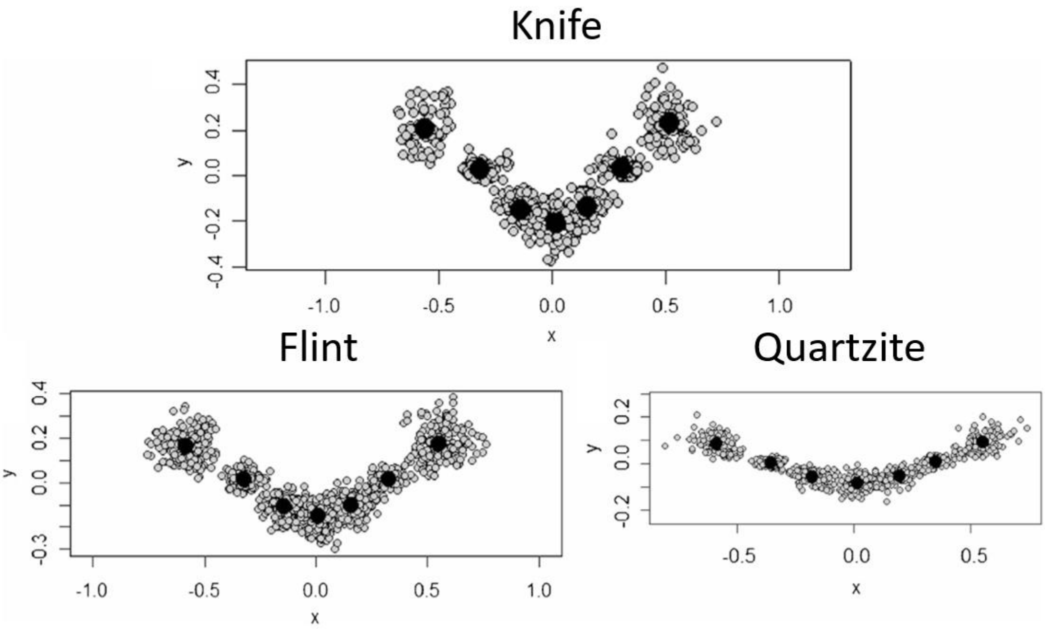
Yravedra, J., Morín, J., Agustí, E. *et al.* (2009) Implicaciones Metalúrgicas de las marcas de corte en la transición Bronce Final-Hierro en el interior de la Península Ibérica. *Gallaecia* **28**, 77–92.

Yravedra, J., Maté-González, M.Á., Palomeque-González, J.F. *et al.* (2017)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. *Boreas* DOI 10.1111/bor.12224.

Supporting Information

Additional Supporting information may be found in the online version of this article at the publisher's website:

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



Sección II: Aplicación experimental al estudio de las marcas de corte

En la sección anterior se ha desarrollado una metodología innovadora para efecturar el estudio de las marcas de corte en hueso. Dicha metodología permite realizar análisis de estas desde una perspectiva métrica, estadística y morfométrica (Maté-González et al., 2015; Palomeque-González et al., 2017). Se ha demostrado que estas técnicas son igualmente resolutivas que las que se realizaban con anterioridad con técnicas microscópicas, al menos en lo que se refiere al estudio de las marcas de corte sobre hueso (Maté-González et al., 2017a).

En esta sección se aplica la metodología anteriormente propuesta de una forma experimental, con el fin de comprobar la validez del método empleado y con el objetivo de ver si existen diferencias significativas entre las marcas de corte producidas por diferentes tipos de herramientas (sílex, cuarcita y metal). Los resultados obtenidos por este tipo de análisis, demuestran que existen diferencias significativas entre las marcas de corte de sílex, cuarcita y metal, y por lo tanto que es posible diferenciar unas marcas de otras (Maté-González et al., 2016a, b).

En esta sección además, se demuestra que existen diferencias significativas entre las marcas de corte producidas por una herramienta y las marcas producidas por dientes de carnívoros, por lo que es posible diferenciar claramente ambos tipos de alteraciones óseas (Maté-González et al., 2016a, b).

Por otro lado, se proponen otros tipos de análisis experimentales con los cuales se estudian marcas de corte producidas por cinco clases de sílex y cinco tipos de cuarcitas diferentes procedentes de distintos lugares de la Península Ibérica (Maté-González et al., 2017b).

Los resultados demuestran que no existen diferencias significativas entre las marcas de corte producidas por distintos tipos de sílex. En lo relativo a las cuarcitas, entre las pertenecientes a la Península Ibérica no existen diferencias significativas entre si, pero sí existen diferencias significativas con las marcas de corte producidas con las cuarcitas de Olduvai (Tanzania), que aunque son geológicamente cuarcitas, más bien parecen cuarzos, lo que ha generado un gran debate sobre si deben ser consideradas cuarcitas o cuarzos (ver Santonja et al., 2014).

Con este estudio se puede afirmar que las marcas de corte producidas por sílex y cuarcita son claramente diferenciables, pero las marcas de corte producidas por diferentes tipos de sílex y diferentes tipos de cuarcitas, entre si, no lo son.

Como consecuencia, podemos decir que los experimentos realizados en este estudio se pueden extrapolar a diversos yacimientos arqueológicos dentro de la

Península Ibérica que contengan sílex y cuarcita entre las materias primas empleadas, ya que al menos las marcas de corte producidas por sílex y cuarcita son claramente diferenciables.

Estos análisis pueden ser de gran utilidad para el estudio de los yacimientos arqueológicos, ya que pueden ayudarnos a determinar con qué tipo de herramienta o útil se aprovecharon los animales que aparecen en los yacimientos.

Artículo 4**:**

Título: **Micro-photogrammetric and morphometric differentiation of cut marks on bones using metal knives, quartzite and flint flakes.**

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Resumen:

En un trabajo previo propusimos un nuevo método alternativo que permitiera analizar las marcas de corte en huesos de animales realizadas con un cuchillo de metal desde una perspectiva métrica y tridimensional (Maté-González et al., 2015). El objetivo de aquel análisis era encontrar una técnica low-cost alternativa a los métodos microscópicos habituales que nos permitiera la reconstrucción tridimensional de marcas de corte junto con sus medidas y secciones asociadas. En este trabajo pretendemos afrontar un estudio experimental más práctico que permita comprobar la validez del método, aplicándolo sobre marcas de corte producidas con un cuchillo de acero inoxidable, lascas de sílex y lascas de cuarcita. Los resultados obtenidos han resultado positivos, permitiendo obtener diferencias entre las marcas de corte producidas por sílex, cuarcita y metal. En este artículo además, se demuestra que existen diferencias significativas entre las marcas de corte producidas por una herramienta y las marcas producidas por dientes de carnívoros, con lo que es posible diferenciar claramente ambos tipos de alteraciones óseas. Estos resultados pueden ser de gran utilidad para el estudio de los yacimientos arqueológicos, ya que pueden ayudarnos a determinar con qué tipo de herramienta o útil se aprovecharon los animales que aparecen en los yacimientos.

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ORIGINAL PAPER

Micro-photogrammetric and morphometric differentiation of cut marks on bones using metal knives, quartzite, and flint flakes

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Abstract In a previous article, we presented an innovative method to analyze cut marks produced with metal tools on animal bones from a metrical and tridimensional perspective (Maté-González et al. 2015). Such analysis developed a low-cost alternative technique to traditional microscopic methods for the tridimensional reconstruction of marks, using their measurements and sections. This article presents the results of an experimental study to test this photogrammetric and morphometric method for differentiating cut marks generated with metal, flint, and quartzite flakes. The results indicate statistically significant differences among cut marks produced by these three types of raw material. These results encourage the application of this method to archeological assemblages in order to establish a link between carcass processing and lithic reduction sequences on different raw materials and also to define the kind of tools used during butchery.

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Keywords Taphonomy · Cut marks · Micro-photogrammetry · Computer vision · Image-based modeling · Raw material

Introduction

Cut marks on bones are the direct evidence of human access to carcass resources. They were first documented in the nineteenth century and the beginning of the twentieth century in some French Paleolithic sites (Lartet 1860; Lartet and Christy 1875; Martin 1909). Since then, cut marks have been recognized in a number of sites of diverse chronology. Gona and Bouri are the locations which yielded the oldest undisputed cut-marked bones, dated to 2.5–2.6 Ma (De Heinzelin et al. 1999; Semaw et al. 2003; Domínguez-Rodrigo et al. 2005), which testified that human beings had processed meat resources at rather early times. Although recently, some claims have been made for earlier butchery traces from two fossils from Dikika (Ethiopia), dated at 3.4 Ma (McPherron et al. 2010; Thompson et al. 2015), this evidence is still controversial and some suggest those traces may have a non-anthropogenic origin (Domínguez-Rodrigo et al. 2010; Domínguez-Rodrigo and Alcalá 2016).

Butchery evidence in the form of cut-marked bone becomes abundant after 2 Ma. Even though it is not possible to define the kind of meat consumption documented in Gona and Bouri, at other locations such as Olduvai, Swartkrans, Koobi Fora, Peninj, Atapuerca, and Ain Hanech, with dates older than a million and a half years, the anatomical distribution of cut marks and their frequencies were key to support that humans had primary access to fleshed carcasses (Domínguez-Rodrigo et al. 2002, 2007, 2009a, 2014a; Pickering et al. 2004; Pobiner et al. 2009; Saladié et al. 2011; Sahnouni et al. 2012). The identification of cut marks was also used to suggest cannibalistic practices on

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different hominines along human evolution (White 1992; Fernández-Jalvo et al. 1996, 1999; Defleur et al. 1999; Bello et al. 2015), increasing the interest and attention of the study of cut marks from fauna to humans. Cut marks are present in the different archeological faunal assemblages regardless of the chronology and species, from large proboscideans (Yravedra et al. 2010, 2012) to micro-mammals, reptiles, and birds (Blasco 2008; Stringer et al. 2008; Blasco and Fernández-Peris 2009, 2012; Finlayson et al. 2012).

Some researchers, aware of the importance of cut marks, have thoroughly considered their microscopic attributes in an attempt to improve their identification, definition, and characterization (e.g., Binford 1981; Bunn 1982; Shipman 1981; Fisher 1995; Domínguez-Rodrigo et al. 2009a, b). Other scholars have performed experimental analyses to describe the differences in cut mark morphology according to the kind of tool or raw material used, i.e., metal or stone (Olsen 1988; Greenfield 1999, 2004, 2006a, b; Bello and Soligo 2008; Yravedra et al. 2009), shell (Choi and Driwantoro 2007), or bamboo (Spennerman 1990; West and Louys 2007). Lithic tool types including simple or retouched flakes and handaxes have also been experimentally used to determine a link between tool type and cut mark type (Walker 1978; Shipman and Rose 1983; Bello et al. 2009; Domínguez-Rodrigo et al. 2009b; De Juana et al. 2010; Galán and Domínguez-Rodrigo 2013). Regarding other alterations, some authors have suggested other features to differentiate cut and tooth marks (Martin 1907; Walker and Long 1977; Shipman 1981, 1988; Binford 1981; Bunn 1982; Fisher 1995; Bromage and Boyde 1984; Andrews and Cook 1985; Cruz Uribe and Klein 1994; Blumenschine et al. 1996; and more). The differentiation of certain alterations such as trampling marks remains problematic as evidenced by the debate concerning the identification of cut marks on deposits of more than 3 Ma (see McPherron et al. 2010 and Thompson et al. 2015 versus Domínguez-Rodrigo et al. 2010 and Domínguez-Rodrigo and Alcalá (2016), as well as the extensive literature on this topic: Andrews and Cook 1985; Behrensmeyer et al. 1986; Olsen and Shipman 1988; Dumbar et al. 1989; Fiorillo 1989; Nicholson 1992; Andrews 1995; Fisher 1995; Blasco et al. 2008; Domínguez-Rodrigo et al. 2009a, b, 2010, 2012; De Juana et al. 2010; Yravedra et al. 2014).

Building on this latter research background, this article presents a new analysis which enables the differentiation between cut marks produced with metal, flint, or quartzite tools. Micro-photogrammetric methodology was used here to reconstruct cut marks from both a metrical and a tridimensional—3D—high-resolution perspective.

This article is the continuation of a previous work (Maté-González et al. 2015), where this new tridimensional method for the analysis of cut marks was presented. In that work, cut marks generated with a metal knife were analyzed to examine shape variability along their sections, and the results showed that if avoiding the ends, cut mark sections were morphologically conservative along most of their trajectory. The present work aims to continue that research applying the technique to cut marks produced with other raw materials such as flint or quartzite, to verify if the micro-photogrammetric and morphometric method is valid to identify tools based on their raw material, determined by the different shape resulting from the degree of thinness in which each material type can produce unmodified cutting tools (i.e., flakes).

Materials and methods

This method incorporates the treatment of high-resolution images with micro-photogrammetry and computer vision for the tridimensional reconstruction of cut-marked sections. Following the methodology discussed in our previous work (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. 1). It was demonstrated that more stable and precise sensors captured better quality images, producing more significant results. Like in the previous work, a Canon EOS 700D reflex camera (Table 1) was used, with 60-mm macro-lenses, which obtained high-resolution and high-quality images.

As our interest was to test the validity of this technique and its applicability to archeological contexts, an experiment with cut marks produced with flint and quartzite tools was developed and subsequently compared with the cut marks generated with a metal knife described in Maté-González et al. (2015).

The experiments followed the same protocol as in the previous work. Hence, cut marks were produced when butchering long bones of young sheep by an expert butcher using simple flint and fine-grained quartzite flakes. The cut marks produced with the knife were the ones described in Maté-González et al. (2015).

Marks were subsequently photographed using a tripod to stabilize the camera as stated in Maté-González et al. (2015). In order to homogenize and optimize lighting conditions, the samples were individually placed on a photographic platform adjusting the light to have the bone permanently well exposed to light. Both exposition time and lighting were kept constant during image capture. To produce referenced 3D models, a millimetrical graphic scale was set next to the cut mark. Photographs were then taken following the specified protocol (Fig. 1). Finally, the images were treated with photogrammetric reconstruction software such as Photogrammetry Workbench (PW) (Fig. 2) (González-Aguilera et al. 2013) or other reconstruction software like Agisoft PhotoScan. Once the 3D models with scales were produced, the Global Mapper software was applied to define mark profiles and measure

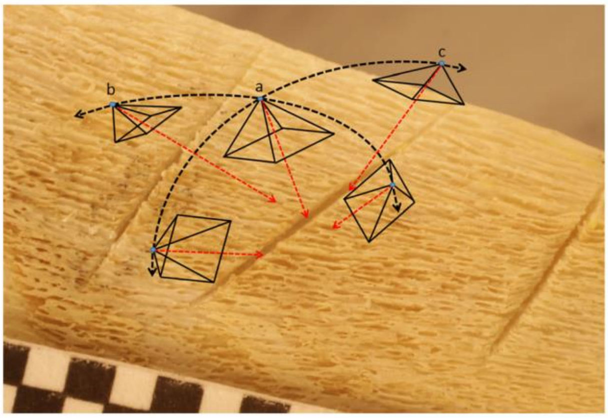


Fig. 1 Protocol for image capture to model a cut mark on a bone by the micro-photogrammetric method, with convergent photographic shots. **a** Master and dependent images in central position, **b** vertical slave images, and **c** horizontal slave images

them (Figs. 3 and 4). Finally, the independent analysis of each cut mark was proposed according to the tool used (Fig. 5) via geometric morphometric analysis. For data collection, a total of 6–10 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 30–45 min 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 versus 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:

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

where $\sigma_{\mathrm{scaling}}$ is the scaling precision established as one third 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 meters per pixel. In this way, it is possible to obtain a comprehensive and complete comparison, at geometric and statistical levels.

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 (Fig. 3).

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. 4 and Table 2) and were taken as quantitative variables. The measurements for each mark section were later compared using a multivariate analysis of principal components (PCA) of the R freeware (www.r-project.org), which estimated similarities and differences of marks on a bidimensional Euclidean space. Plotting of the PCA results with confidence ellipses was made with the ggplot2 R library.

The geometric morphometric analysis was performed as well as a generalized procrustes analysis (GPA) as a complement to the multivariate metric analysis (Fig. 4). In this case, a morphometric analysis approach was applied, based on seven identical landmarks per section—as shown in Fig. 4 (LM 1–7)—which were considered from each mark using the tpsUtil (v. 1.60.) and tpsDig2 (v.2.1.7) programs, following Maté-González et al. (2015). The location of the seven landmarks respond to the measures considered for the statistical analysis, as seen in Fig. 4. Thus, 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 end of the mark. LM4 was at the very end, and LM5, LM6, and LM7 were in opposed positions to LM3, LM2, and LM1 (Fig. 4). The resulting tps file was imported to R and analyzed via the "geomorph" library (Sherratt 2014).

Lastly, the estimation of the existence or not of differences among the several groups of marks defined by raw materials was performed through a discriminate lineal analysis. The lda

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

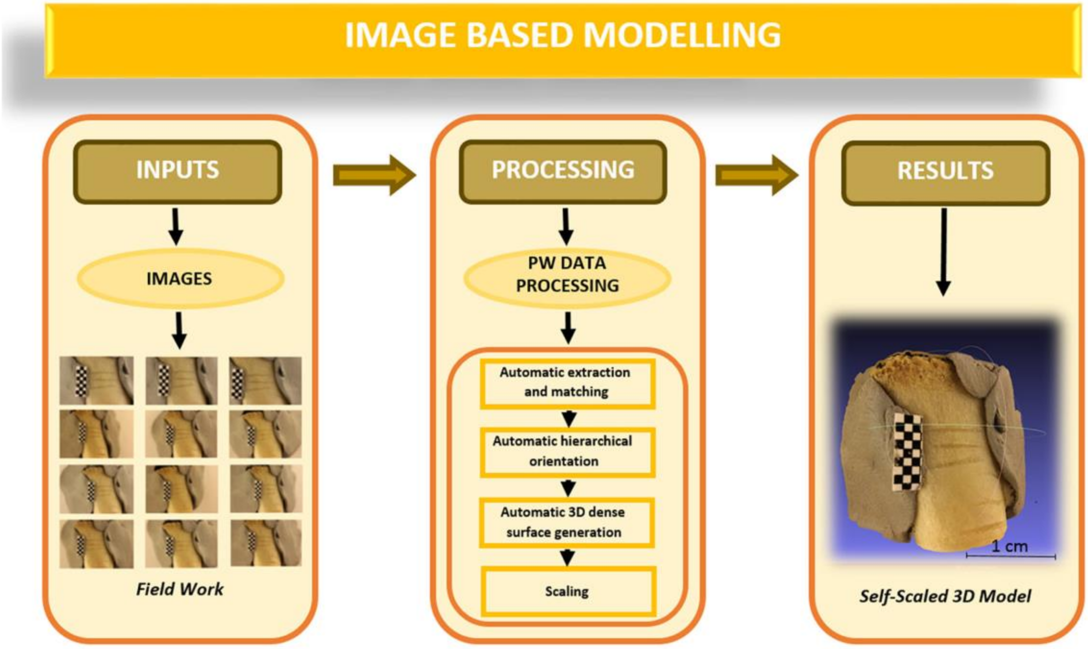


Fig. 2 Workflow of the image-based modeling technique

function included in the MASS (XX2) pack in the R statistical program was used.

Experimental results

The micro-photogrammetric analysis enabled the differentiation between cut marks produced with flint and quartzite flakes and metal knives, due to divergent mark section shapes caused by differences in the edge morphology of the flakes of both stone raw materials and the metal knife.

From a qualitative perspective, Fig. 5 shows that metal-produced cut marks were deeper and narrower than the ones generated both with flint and quartzite flakes. Additionally, cut marks made with flint were narrower and deeper than the ones with quartzite (Fig. 5). These results were similar to the ones observed previously (Walker and Long 1977; Walker 1978). Marks produced with metal tools described rectilinear and highly uniform traces which usually did not present the

Fig. 3 Representation of the *A–G* sections of the cut mark regarding its length

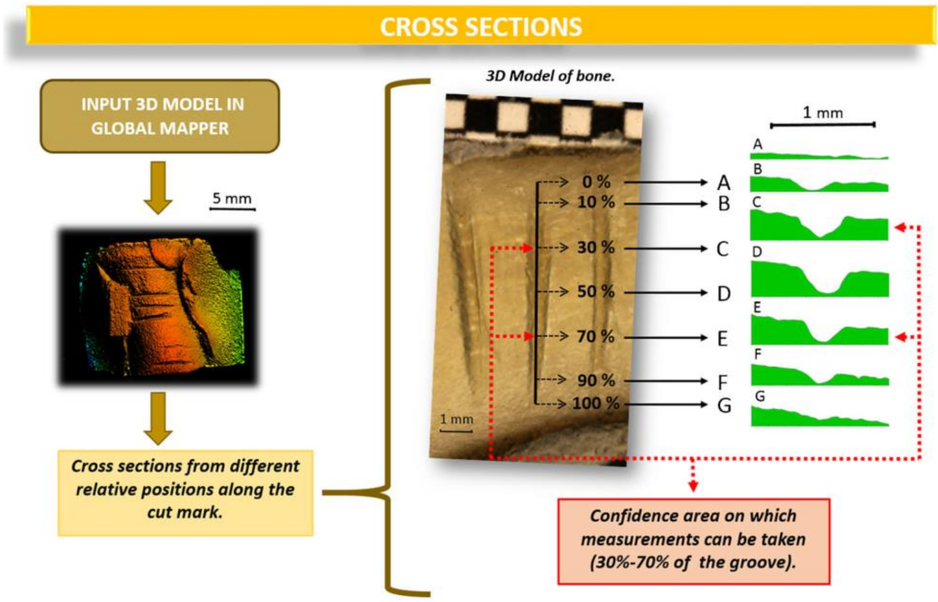
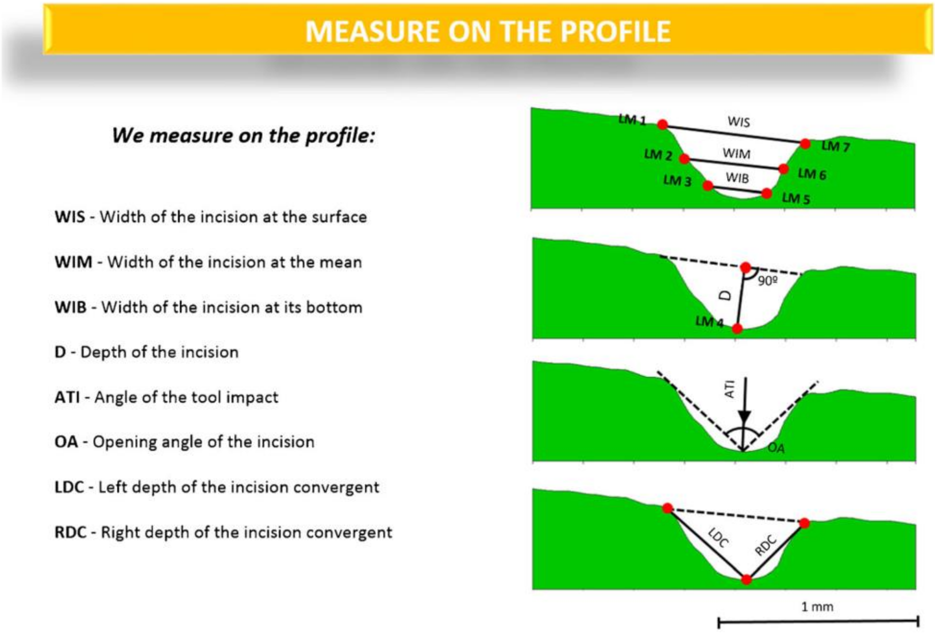


Fig. 4 Location of measurements sensu Bello et al. (2013). Landmarks (*LM1–7*) used for the morphometric model are also represented



micro-striations typical of lithic tools. Marks made with flint flakes had a V section, like the ones made with metal, but this was more open, with a wider upper section (Fig. 5). Quartzite flakes produced V-shaped sections as well, but they were even wider and shallower than those made with flint flakes (Fig. 5).

The 95 % confidence ellipses of the PCA of the measurements (Table 2) specified in Fig. 4 presented a clear difference between quartzite and metal-produced marks (Fig. 6). Flint marks were plotted in the middle of both patterns. Even though some areas overlapped, in a large number of cases it was possible to relate each mark to a specific tool (see below the percentage of correct classification). The three types of marks were quite different when metal and flint (Fig. 6), quartzite and flint (Fig. 6), and metal and quartzite (Fig. 6) were compared pairwise; in the latter, differences were even more significant.

Fig. 5 Cut marks generated with a metal knife, and a quartzite and flint flake. Detail for the V sections in the three types of marks

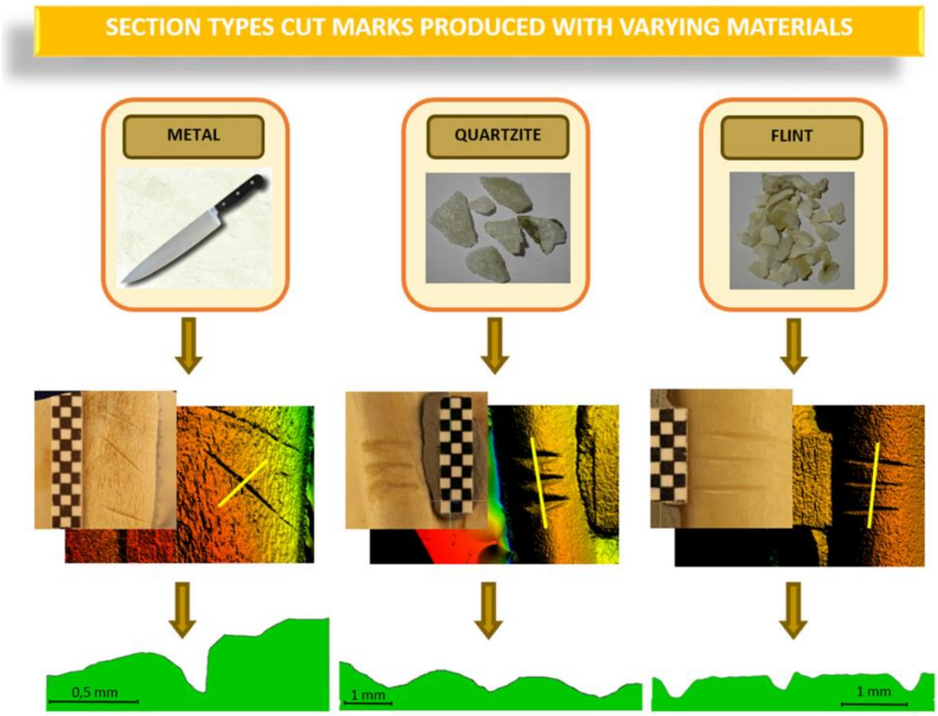


Table 2 Measurements used to characterize cut mark sections, as described in Fig. 2

WIS	Width of the incision at the surface
WIM	Width of the incision at the mean
WIB	Width of the incision at its bottom
OA	Opening angle of the incision
D	Depth of the incision
LDC	Left depth of the incision convergent
RDC	Right depth of the incision convergent
ATI	Angle of the tool impact

By using the morphometric GPA and the geomorph pack (Palomeque-González et al. 2016) with the seven landmarks (Fig. 4), the silhouettes of all the cut marks produced by the different raw materials were reconstructed (Fig. 7): marks produced with metal (Fig. 7a), flint (Fig. 7b), and quartzite (Fig. 7c). These morphometric reconstructions clearly showed that metal marks were narrower and deeper than flint marks, and the latter were in turn deeper and narrower than quartzite marks, which were consequently the wider and the shallower marks in the sample with respect to width.

Finally, the results from GPA were analyzed by PCA including all raw materials (Fig. 8). All the points representing marks produced with quartzite flakes (green) clustered together; flint (black) and metal (red) were similarly clearly clustered in independent groups. The deformation network depicted the same tendencies noted in previous tests. There was a definite order according to the raw material used.

These analyses evidenced that cut marks produced with flint, quartzite, and metal tools were morphologically different. However, some overlapping was noted in some cases (Figs. 6), particularly between flint and metal (Fig. 6) and flint and quartzite (Fig. 6). In order to estimate the relevance of this overlapping, a discriminate lineal analysis of the cut marks values was performed. A confusion matrix for each individual group was developed, concluding that there was no confusion between the marks made with quartzite and metal (Table 3), an observation which confirmed the situation observed in Fig. 8. This analysis aimed to define the percentage of total marks that was well classified in each group and their misclassification frequency. The study also underlines that morphometric analyses (Figs 7 and 8) provide a better differentiation in the use of different raw materials when comparing cut marks than biometrics (Fig. 6).

According to the confusion matrix, 81.5 % of flint-produced marks, 53 % of metal ones, and 61.6 % of quartzite were accurately classified. Summing up, the rate of correct classification in this experimental assemblage was about 70 %, which proved that in most cases it was possible to distinguish among the different raw materials used to cut the bones.

Discussion

Microscopic categorization of cut marks made with simple flakes, retouched flakes, and even handaxes yielded a high rate of correct classification (and, hence, identification) even when compared with non-anthropogenic marks (e.g., trampling marks) using a multivariate combination of microscopic feature variables (Domínguez-Rodrigo et al. 2009b; De Juana et al. 2010). Recent replication of some of these studies only achieved partial success in replicating differences between cut

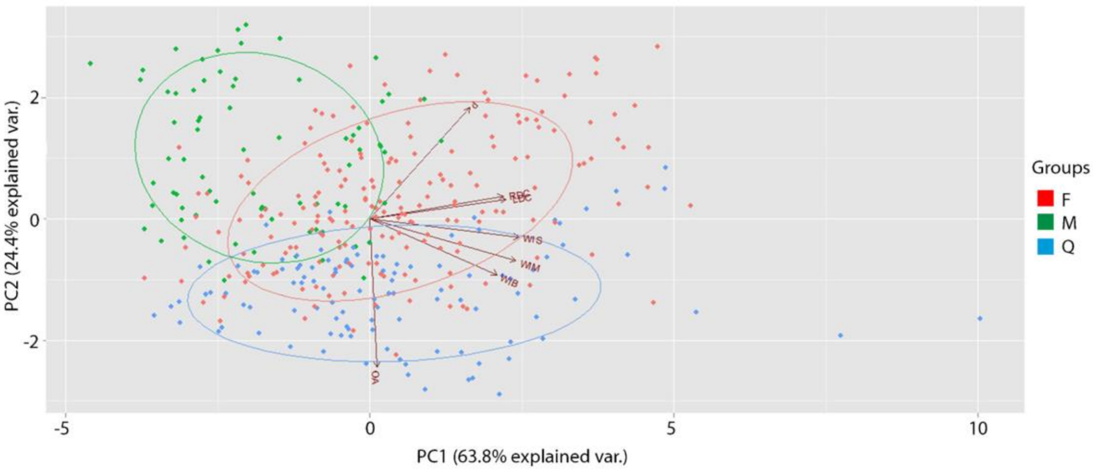


Fig. 6 Principal component analysis (PCA) of cut marks produced with metal (*M*), flint (*F*), and quartzite (*Q*) tools

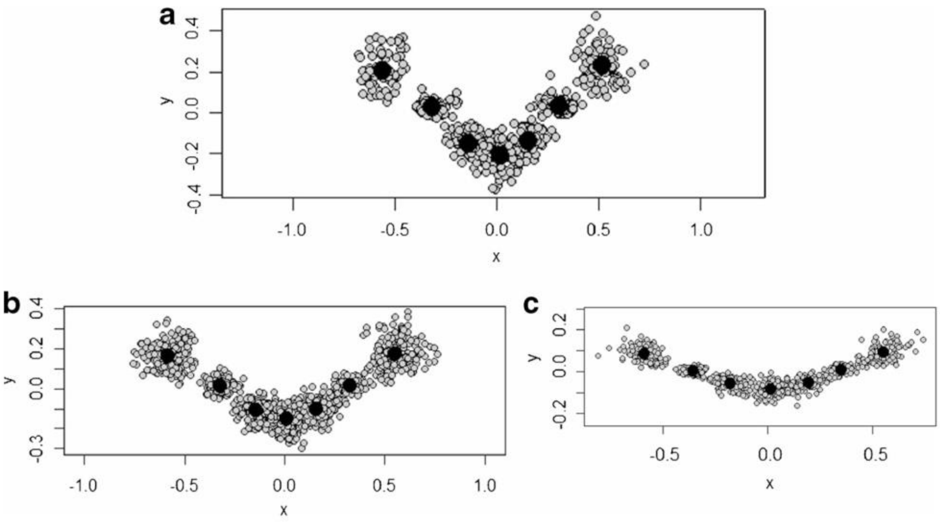


Fig. 7 Silhouettes of cut marks produced with a metal knife (**a**), a flint flake (**b**), and a quartzite flake (**c**). The *black points* are the centroids associated to each landmark

and trampling marks (Monnier and Bischoff 2014). This is mostly due to a methodological artifact: purported trampling was experimentally reproduced in a tumbler containing rocks and a bone (Monnier and Bischoff 2014). This was not done with sediment as trampling is commonly understood and experimentally reproduced (i.e., effectors = sand or gravel; actor = organism applying strength on bone surface via the effectors). The Monnier and Bischoff (2014) experiment produced bone abrasion by prolonged bone-rock friction rather than by the much more intense punctual pressure that trampling agents (e.g., mammal individual stepping on a bone) produce during discrete bone modification episodes. Thus, what Monnier and Bischoff (2014) have shown is that natural processes mimicking continuous friction of a bone with a rock (probably through encasing both elements in the same sedimentary context), which is different from trampling, may result in some (but not all) the microscopic features that discriminate trampling marks from cut marks. This should not come as a surprise. Behrensmeyer et al. (1986) already noticed that continuous friction of a bone with marks against a sedimentary matrix even for periods of time as brief as 3 min resulted in the loss of resolution, with specifically diagnostic characteristics, such as internal groove micro-striations, being lost during the abrasion caused by this continuous sedimentary friction process.

Some authors have built upon two-dimensional diagnosis of cut marks by incorporating features that are only observable in a three-dimensional setting (Bello and Soligo 2008; Bello et al. 2009; Bello 2011; Bonney 2014). The combination of the new three-dimensional diagnosis with the two-dimensional referential frameworks strengthens our ability to differentiate and identify marks when analyzing archeofaunal assemblages. However, in some respects, this recent three-dimensional approach to the study of bone surface

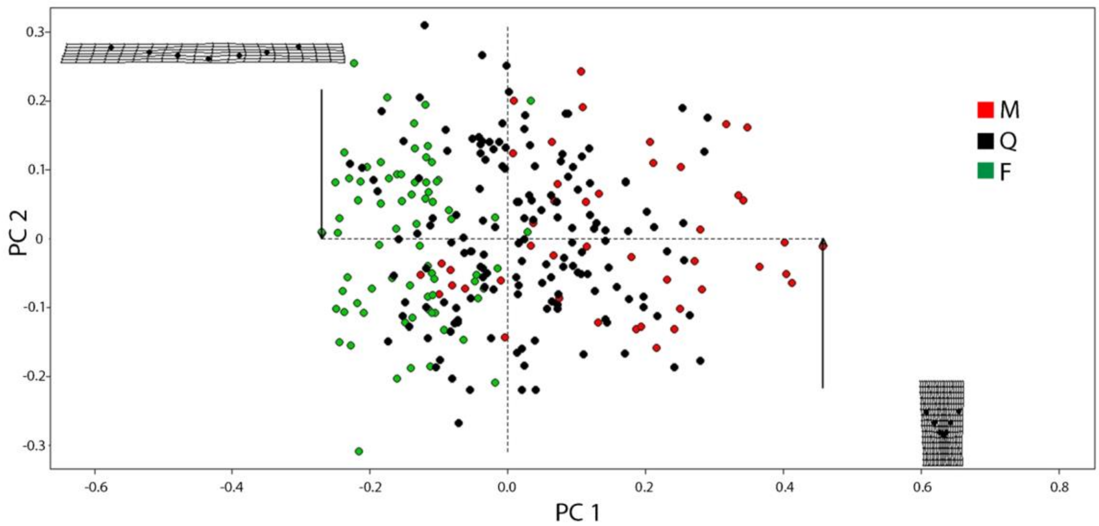


Fig. 8 PCA of the GPA, where quartzite-related marks are in *green*, flint ones in *black*, and metal in *red*

Table 3 Confusion matrix for each individual group showing the number of correctly classified marks (diagonal) and those that were incorrectly classified

	F	M	Q
F	154	12	23
M	35	40	0
Q	41	0	66

F flint, *M* metal, *Q* quartzite

modifications still requires methodological definition and experimental contrasting. For instance, it would be interesting to compare methods for their resolution. Likewise, it would be important to compare cut marks and any other non-anthropogenic mark, such as trampling mark or teeth mark, in 3D to document if the resulting diagnosis is as heuristic as when using a bidimen sional approach. This would shed some light to the debate cut versus trampling marks 3 Ma ago (McPherron et al. 2010; Thompson et al. 2015 versus Domínguez-Rodrigo et al. 2010; Domínguez-Rodrigo and Alcalá 2016.). Unfortunately, we have not achieved the optimal resolution to replicate trampling sections in 3D and thus we have not been able to perform an analysis with a high degree of resolution. In the case of inconspicuous marks or trampling, SEM provides a higher degree of resolution, and thus three-dimensional reconstructions with SEM are suitable to questionable marks. Nevertheless, our methodology has proven to be operative in response to specific questions applied to certain types of marks, such as the identification of the raw material used in the processing of carcasses. Even when comparing cut marks—regardless of the raw material used—with tooth marks such as scores—produced by different carnivores—the technique is operative. Thus, in Figs. 9 and 10, it is possible to distinguish both types of marks.

The analytical method presented here complements other powerful three-dimensional microscopic approaches to the study of cut marks (e.g., Bello and Soligo 2008; Bello et al. 2009; Bello 2011). The three-dimensional approach holds a type of information that has enabled addressing questions like those in the present study that were impossible to answer using a two-dimensional approach. Differentiating among same (flakes) or similar (flake versus knife) tools made on different raw material types was impossible until a proper understanding of a 3D micro-topography of bone surfaces and marks was available. Even though this method presents some limitations, it must be taken into account that it is a new methodology that can be improved. This opens a new window to new questions that will ultimately link the lithic record of any given assemblage (and the differential reduction sequences represented in it via different types of raw materials) and the butchery process.

Conclusions

The study of cut marks holds potential information for our understanding of human behavior in past human societies. Experiments to identify butchery behavior should be particularly emphasized. Among them, the

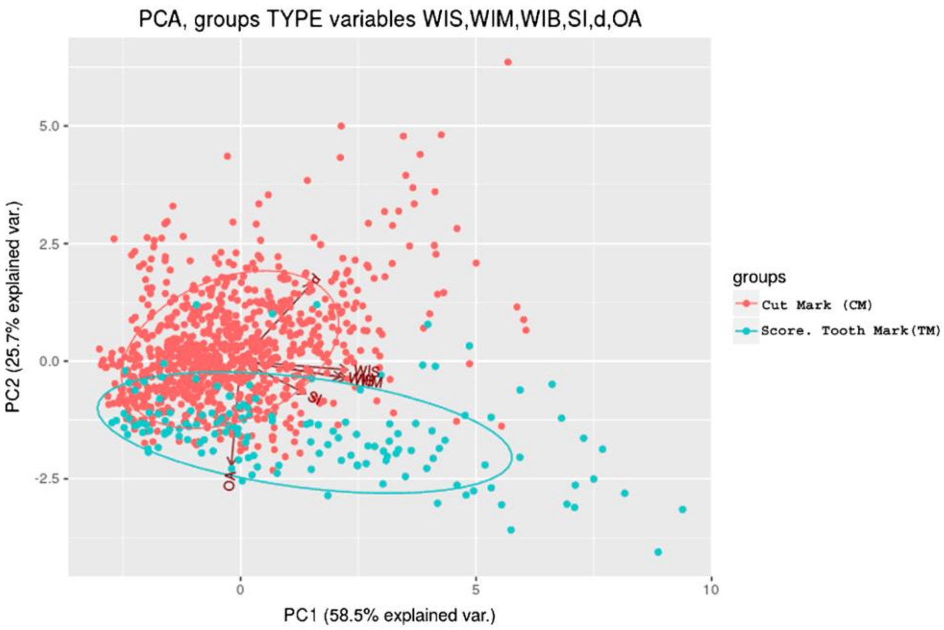


Fig. 9 Principal component analysis (PCA) of cut marks produced with several raw material and scores generated for several carnivores

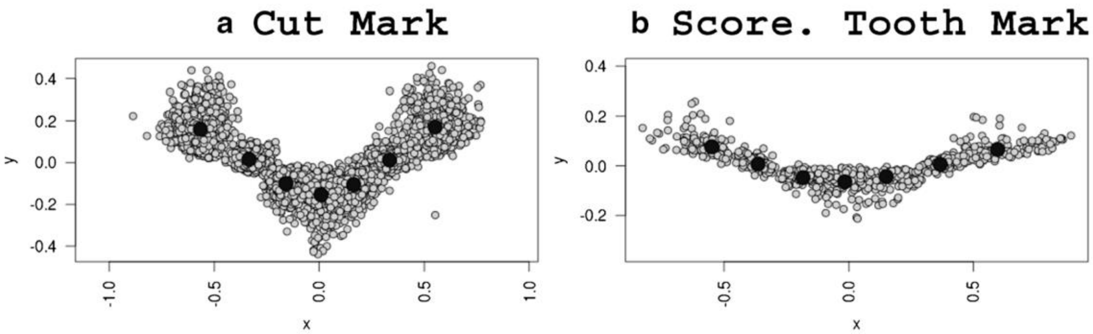


Fig. 10 Silhouettes of cut marks produced with several raw material (**a**) and silhouettes of scores produced for several carnivores (**b**). The *black points* are the centroids associated to each landmark

analysis leading to the discrimination of the raw materials and/or tools used for butchering in archeological sites is of great interest (Greenfield 1999, 2004, 2006a, b; Choi and Driwantoro 2007; Bello et al. 2009). The difference of the present work and previous studies lies in the methodology used for mark identification. Most methods used for cut mark morphology analysis are restricted to optic microscopy, hand lenses and SEM (Shipman 1981; Olsen 1988; Greenfield 1999, 2004, 2006a,b; Smith and Brickley 2004; Lewis 2008), binocular microscope for high-resolution pictures (Domínguez-Rodrigo et al. 2009a, b; De Juana et al. 2010; Marín-Monfort et al. 2014), digital imaging techniques (Gilbert and Richards 2000), 3D reconstruction (Bartelink et al. 2001; During and Nilsson 1991; Kaiser and Katterwe 2001), 3D digital microscope (Boschin and Crezzini 2012; Crezzini et al. 2014), and a recent technique based on the use of Alicona 3D Infinite Focus Imaging microscope (Bello and Soligo 2008; Bello et al. 2009; Bello 2011; Bonney 2014). The technique proposed here incorporates a low-cost methodology based on the treatment of high-resolution images with micro-photogrammetry and computer vision for tridimensional reconstruction of cut marks on bones (Maté González et al. 2015.

The models developed through the micro-photogra mmetric 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 high precision. It has been applied to a group of cut marks produced with different raw materials—quartzite and flint flakes, and metal knife—with positive results which provided several evidence guidelines to discriminate cut marks according to the raw material used. Thus, morphological differences among the three raw materials considered were detected (Fig. 5), as well as statistical (Figs. 6) and morphometric deviations (Fig. 7), particularly when morphometry was combined with standardizing methods (Fig. 8). The results coincide with Walker and Long (1977), Walker (1978), Greenfield (1999, 2006b), or Boschin and Crezzini (2012) observations of the contrast between cut marks produced with metal and lithic tools; however, in this analysis a larger sample was used.

All the cut marks observed presented a V section, but metal ones were narrower and deeper, morphometrically different from quartzite marks (Figs. 5, 6, 8, and 10c). Flint marks, in turn, were deeper and narrower than quartzite marks, but not as evident as the ones produced with a metal knife. In morphometric terms, they were in an intermediate position between the quartzite and the metal marks, but different enough to be discriminated from the marks produced with those raw materials (Figs. 5, 6, 7, 8, and 10a). On the other hand, if certain adjustments were made to the measurement procedure, by discriminating among the most diagnostic variable, an improvement in the identification of each kind of mark as well as in the resolution of the method could be possible.

These results proved the usefulness of this methodology when applied to cut marks produced with different raw materials. They showed a high resolution, and although some overlapping was observed between marks, differences among the three kinds of marks were clear, with a more notorious discrimination between quartzite and metal.

This method offers similar benefits to more traditional methods while having some advantages. Firstly, it is a low-cost technique; it does not need sophisticated technical equipments such as microscopes. Secondly, its application does not require much processing time, making it possible to analyze larger samples in a shorter time, including even the complete faunal assemblage, and the technique can be reproduced.

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References

Andrews P (1995) Experiments in taphonomy. J Archaeol Sci 22:147–153

Andrews P, Cook J (1985) Natural modifications to bones in a temperate setting. Man 20:675–691

Bartelink EJ, Wiersema JM, Demaree RS (2001) Quantitative analysis of sharp-force trauma: an application of scanning electron microscopy in forensic anthropology. J Forensic Sci 46:1288–1293

Behrensmeyer AK, Gordon KD, Yanagi GT (1986) Trampling as a cause of bone surface damage and pseudo-cutmarks. Nature 319:768–771

Bello SM (2011) New results from the examination of cut-marks using three-dimensional imaging. In: Ashton N, Lewis SG, Stringer C (eds) The ancient human occupation of Britain. The Netherlands, Amsterdam, pp. 249–262

Bello SM, Soligo C (2008) A new method for the quantitative analysis of cutmark micromorphology. J Archaeol Sci 35:1542–1552

Bello SM, Parfitt SA, Groote I, Kennaway G (2013) Investigating experimental knapping damage on an antler hammer: a pilot-study using high-resolution imaging and analytical techniques. J Archaeol Sci 40:4528–4537

Bello SM, Parfitt SA, Stringer CB (2009) Quantitative micromorphological analyses of cut marks produced by ancient and modern handaxes. J Archaeol Sci 36:1869–1880

Bello SM, Saladié P, Cáceres I, Rodríguez-Hidalgo A, Parfitt SA (2015) Upper Palaeolithic ritualistic cannibalism: Gough's Cave (Somerset, UK): the human remains from head to toe. J Hum Evol 82:170–189

Binford LR (1981) Bones: ancient men, modern myths. Academic press, New York

Blasco R (2008) Human consumption of tortoises at Level IVof Bolomor Cave Valencia, Spain. J Archaeol Sci 35:2839–2848

Blasco R, Fernández Peris J (2009) Middle Pleistocene bird consumption at Level XI of Bolomor Cave Valencia, Spain. J Archaeol Sci 36:2213–2223

Blasco R, Fernández Peris J (2012) A uniquely broad spectrum diet during the Middle Pleistocene at Bolomor Cave, Valencia, Spain. Quat Int 252:16–31

Blasco R, Rosel J, Fernández Peris J, Cáceres I, Vergès JM (2008) A new element of trampling: an experimental application on the Level XII faunal record of Bolomor Cave (Valencia, Spain). J Archaeol Sci 35: 1605–1618

Blumenschine RJ, Marean C, Capaldo S (1996) Blind test of inter-analyst correspondence and accuracy in the identification of cut marks. Percusion marks and carnivore tooth marks on bone surface Journal of Archaeological Sciencie 23:493–505

Bonney H (2014) An investigation of the use of discriminant analysis for the classification of blade edge type from cut marks made by metal and bamboo blades. Am J Phys Anthropol 154:575–584

Boschin F, Crezzini J (2012) Morphometrical analysis on cut marks using a 3D digital microscope. Int J Osteoarchaeol 22:549–562

Bromage TG, Boyde A (1984) Microscopic criteria for the determination of directionality of cutmarks on bone. Am J Phys Anthropol 65: 359–366

Bunn HT (1982) Meat eating and human evolution: studies on the diet and subsistence patterns of Plio-Pleistocene hominids in East Africa. Dissertation, University of California, Berkeley, Ph. D

Choi K, Driwantoro D (2007) Shell tool use by early members of Homo erectus in Sangiran, central Java, Indonesia: cut mark evidence. J Archaeol Sci 34:48–58

Crezzini J, Boschin F, Boscato P, Wierer U (2014) Wild cats and cut marks: exploitation of *Felis silvestris* in the Mesolithic of Galgenbühel/Dos de la Forca (South Tyrol, Italy). Quat Int 330:52–60

Cruz Uribe K, Klein RG (1994) Chew marks and cut marks on animal bones from the Kastelberg B and Dune field Middle Later Stone Age sites, Western Cape Province, Soyth Africa. J Archaeol Sci 21:35–49

De Heinzelin J, Clark JD, White T, Hart W, Renne P, Wolde Gabriel G, Beyene Y, Vrba E (1999) Environment and behavior of 2.5–million–year-old Bouri hominids. Science 284:625–629

De Juana S, Galán AB, Domínguez-Rodrigo M (2010) Taphonomic identification of cut marks made with lithic handaxes: an experimental study. J Archaeol Sci 37:1841–1850

Defleur A, White T, Valensi P, Slimak L, Crégut-Bonnoure E (1999) Neanderthal cannibalism at Moula-Guercy, Ardèche, France. Science 286:128–131

Domínguez-Rodrigo M, Alcalá L (2016) 3.3-Million-year-old stone tools and butchery traces? More evidence needed. PaleoAnthropology 2016:46–53. doi:10.4207/PA.2016.ART99

Domínguez-Rodrigo M, Barba R, Egeland CP (2007) Deconstructing Olduvai. Springer Books, Netherland, A taphonomic study of the Bed I sites

Domínguez-Rodrigo M, Pickering TR, Bunn HT (2012) Experimental study of cut marks made with rocks unmodified by human flaking and its bearing on claims of 3.4-million-year-old butchery evidence from Dikika, Ethiopia. J Archaeol Sci 39:205–214

Domínguez-Rodrigo M, Bunn HT, Yravedra J (2014) A critical re-evaluation of bone surface modification models for inferring fossil hominin and carnivore interactions through a multivariate approach: application to the FLK Zinj archaeofaunal assemblage (Olduvai Gorge, Tanzania). Quat Int 322-23:32–43

Domínguez-Rodrigo M, de Juana S, Galán AB, Rodríguez M (2009b) A new protocol to differentiate trampling marks from butchery cut marks. J Archaeol Sci 36:2643–2654

Domínguez-Rodrigo M, de la Torre I, Luque L, Alcalá L, Mora R, Serrallonga J, Medina V (2002) The ST site complex at Peninj, West Lake Natron, Tanzania: implications for early hominid behavioural models. J Archaeol Sci 29:639–665

Domínguez-Rodrigo M, Mabulla A, Bunn HT, Barba R, Diez-Martín F, Egeland CP, Espílez E, Egeland A, Yravedra J, Sánchez P (2009a) Unraveling hominin behavior at another anthropogenic site from Olduvai Gorge (Tanzania): new archaeological and taphonomic research at BK, Upper Bed II. J Hum Evol 57:260–283

Domínguez-Rodrigo M, Pickering TR, Bunn HT (2010) Configurational approach to identifying the earliest hominin butchers. Proceedings of the National Academy of Sciences USA 107 (49): 20929–20934. Domínguez-Rodrigo M, Pickering, T.R., and Bunn, H.T. 2012. Experimental study of cut marks made with rocks unmodified by human flaking and its bearing on claims of 3.4 million-year-old butchery evidence from Dikika, Ethiopia. J Archaeol Sci 39:205–214

Domínguez-Rodrigo M, Pickering TR, Semaw S, Rogers M (2005) Cutmarked bones from archaeological sites at Gona, Afar, Ethiopia: implications for the function of the world's oldest stone tools. J Hum Evol 48:109–121

Dumbar JS; Webb D., Cring, D (1989) Cultural and non cultural modified bone and inundated paleoindian sites in the arcilla River, North Florida: an indicator of site integrity En Bonnichsen abd Modification. Centre for the study of the First American. Orono, 99–120

During EM, Nilsson L (1991) Mechanical surface analysis of bone: a case study of cut marks and enamel hypoplasia on a Neolithic cranium from Sweden. Am J Phys Anthropol 84:113–125

Fernández-Jalvo Y, Díez JC, Bermúdez de Castro JM, Carbonell E, Arsuaga J (1996) Evidence of early cannibalism. Science 271: 277–278

Fernández-Jalvo Y, Díez JC, Cáceres I, Rosell J (1999) Human cannibalism in the early Pleistocene of Europe (Gran Dolina, Sierra de Atapuerca, Spain). J Hum Evol 37:591–622

Finlayson C, Brown K, Blasco R, Rosell J, Negro J (2012) Birds of a feather: Neanderthal exploitation of raptors and corvids. PLoS One 79:45927

Fiorillo AR (1989) An experimental study of trampling: implications for the fossil record. In: Bonnichsen R, Sorg M (eds) Bone Modification. University of Maine Centre for the Study of the First Americans, Orono, pp. 61–75

Fisher DC (1995) Bone surface modifications in zooarchaeology. J Archaeol Method Theory 2:7–65

Galán AB, Domínguez-Rodrigo M (2013) An experimental study of the anatomical distribution of cut marks created by filleting and disarticulation on the long bone ends. Archeometry 55:1132–1149

Gilbert WH, Richards GD (2000) Digital imaging of bone and tooth modification. Anat Rec 261:237–246

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).

Greenfield HJ (1999) The origins of metallurgy: distinguishing stone from metal cut-marks on bones from archaeological sites. J Archaeol Sci 26:797–808

Greenfield HJ (2004) The butchered animal bone remains from Ashqelon, Afridar-Area G. Antiqot 45:243–261

Greenfield HJ (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 HJ (2006b) Slicing cut marks on animal bones: diagnostics for identifying stone tool type and raw material. Journal of Field Archaeology 31:147–163

Kaiser TM, Katterwe H (2001) The application of 3D-Microprofilometry as a tool in the surface diagnosis of fossil and sub-fossil vertebrate hard tissue. An example from the Pliocene Upper Laetoli Beds, Tanzania. Int J Osteoarchaeol 11:350–356

Lartet E (1860) On the coexistence of man with certain extinct quadrupeds, proved by fossil bones from various Pleistocene deposits, bearing incisions made by sharp instruments. Quarterly Journal of the sociological society of London 16:471–479

Lartet E, Christy H (1875) Reliquiae Acquitanicae being contributions to the archaeology and paleontology of Perigord and adjoining provinces of Southern France. London Willians and Nagorte, London

Lewis JE (2008) Identifying sword marks on bone: criteria for distinguishing between cut marks made by different classes of bladed weapons. J Archaeol Sci 35:2001–2008

Luhmann T, Robson S, Kyle S, Boehm J (2013) Close-range photogrammetry and 3D imaging. Walter De Gruyter, Berlin

Marín-Monfort MD, Pesquero MD, Fernández-Jalvo Y (2014) Compressive marks from gravel substrate on vertebrate remains: a preliminary experimental study. Quat Int 330:118–125

Martin H. (1907) Presentation d'ossements utilises de l'epoque Musterienne en Bourlon M. M. Giraux L. & Martin H. (1907). Un os utilise presolutrean a propos de os utilises Communique Faites a la société Prehistorica de la France le 23 mai 1907.8–16

Martin H (1909) Desarticulation des quelques regions chez les rumiants et le cheval a l'epoque mousterienne. Bulletin de la Societé Préhistorique Française 7:303–310

Maté González MA, Yravedra J, González-Aguilera D, Palomeque-González JF, Domínguez-Rodrigo M (2015) Micro-photogrammetric characterization of cut marks on bones. J Archaeol Sci 62:128–142

McPherron SP, Alemseged Z, Marean CW, Wynn JG, Reed D, Geraads D, Bobe R, Béarat HA (2010) Evidence for stone-tool-assisted consumption of animal tissues before 3.39 million years ago at Dikika, Ethiopia. Nature 466:857–860

Monnier GF, Bischoff E (2014) Size matters. An evaluation of descriptive and metric criteria for identifying cut marks made by unmodified rocks during. J Archaeol Sci 50:305–317

Nicholson RA (1992) Bone survival the effects of sedimentary abrasion and trampling on fresh and cooked bone. Int J Osteoarchaeol:2: 79–2: 90

Olsen SL (1988). The identification of stone and metal tool marks on bone artefact BAR 452: 337–360.

Olsen SL, Shipman P (1988) Surface modification on bone: trampling vs butchery. J Archaeol Sci 15:535–553

Palomeque-González JF, San Juan-Blazquez M, Maté-González MA, Yravedra J, García-Vargas E, Martín-Perea DM, González-Aguilera D, Domínguez-Rodrigo M (2016) Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones. Int J Osteoarchaeol (in Press)

Pickering T, Domínguez-Rodrigo M, Egeland CP, Brain CK (2004) New data and ideas on the foraging behavior of Early Stone Age hominids at Swartkrans Cave. South Africa South African Journal of Science 100:215–218

Pobiner BL, Rogersb MJ, Monahan CM, Harrisd JWK (2009) New evidence for hominine carcass processing strategies at 1.5 Ma, Koobi Fora, Kenya. J Human Evolution 55:103–130

Sahnouni M, Rosell J, Van der Made J, Vergès JM, Ollé A, Kandi N, Harichane Z, Derradji A, Medig M (2012) The first evidence of cut marks and usewear traces from the Plio-Pleistocene locality of El-Kherba (Ain Hanech), Algeria: implications for early hominin subsistence activities circa 1.8 Ma. J Human Evolution 64:137–150

Saladié P, Huguet R, Díez C, Rosell J, Cáceres I, Rodríguez-Hidalgo A, Vallverdú J, Bermúdez de Castro JM, Carbonell E (2011) Carcass transport decisions in Homo antecessor subsistence strategies. J Human Evolution 61:425–446

Semaw S, Rogers MJ, Quade J, Renee PR, Butler RF, Stout D, Domínguez-Rodrigo M, Hart W, Pickering T, Simpson SW (2003) 2.6-Million-year-old stone tools and associated bones from OGS-6 and OGS-7, Gona, Afar, Ethiopia. J Human Evolution 45:169–177

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 (1981) Life historia of a fossil. Harvard University Press, An Introduction to Taphonomy and Paleoecology

Shipman, P. (1988). Actualistic studies of animal and hominid activities In Olsen Sl. 261–285. En Olsen S. L. Scaning electron microscopy in Archaeology. BAR 452. Oxford.

Shipman P, Rose J (1983) Early hominid hunting, buchering and carcass-processing behaviours: a roaches to tha fosil record. J Anthropol Archaeol 2:57–98

Smith MJ, Brickley MB (2004) Animals and interpretation of flint toolmarks found on bones from West Tump Long Barrow, Gloucestershire. Int J Osteoarchaeol 14:18–33

Spennerman DHR (1990) Don't forget the bamboo on recognising and interpretating butchery narcks in tropical faunal assemblages some comments asking for cauting. Solomon S Davidson I Watson D (eds) Problems Solving Taphonomy Tempus 2:80–101

Stringer C, Finlayson C, Barton RNE, Fernández-Jalvo Y, Cáceres I (2008) Neanderthal exploitation of marine mammals in Gibraltar. Proc Natl Acad Sci 10538:14319–14324

Thompson JC, McPherron S, Bobe R, Reed D, Barr A, Wynn J, Marean CW, Geraads D, Alemseged Z (2015) Taphonomy of fossils from the hominin-bearing deposits at Dikika, Ethiopia. J Hum Evol 86:112–135

Walker PL (1978) Butchering and stone tool function. Am Antiq 43:710–715

Walker PL, Long JC (1977) An experimental study of the morphological characteristics of cut marks. Am Antiq 42:605–616

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. J Archaeol Sci 34:512–518

White TD (1992) Prehistoric cannibalism at Mancos 5MTUMR-2346. Princeton University Press, Princeton

Yravedra J, Domínguez-Rodrigo M, Santonja M, Pérez-González A, Panera J, Rubio-Jara S, Baquedano E (2010) Cut marks on the Middle Pleistocene elephant carcass of Áridos 2 (Madrid, Spain). J Archaeol Sci 37:2469–2476

Yravedra J, Morín J, Agustí E, Sanabria P, López M, Urbina D, López-Frailes FJ, López G, Illán Illán J (2009) Implicaciones Metalúrgicas de las marcas de corte en la transición Bronce Final-Hierro en el interior de la Península Ibérica. Gallaecia 28:77–92

Yravedra J, Panera J, Rubio-Jara S, Manzano I, Expósito A, Pérez-González A, Soto E, López-Recio M (2014) Neanderthal and *Mammuthus* interactions at EDAR Culebro 1 (Madrid, Spain). J Archaeol Sci 42:500–508

Yravedra J, Rubio-Jara S, Panera J, Uribelarrea D, Pérez-González A (2012) Elephants and subsistence. Evidence of the human exploitation of extremely large mammal bones from the Middle Palaeolithic site of PRERESA (Madrid. Spain Journal of Archaeological Science 39:1063–1071

Artículo 5:

Título: **Flint and quartzite: Distinguishing raw material through bone cut marks.**

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Resumen:

Desde los años ochenta, algunos autores han caracterizado y diferenciado las marcas de corte que producen diferentes tipos de materia prima como el sílex, la obsidiana, el metal o la cuarcita (Olsen 1988; Greenfield, 1999, 2004, 2006a, b; Bello y Soligo, 2008; Yravedra et al., 2009), la concha (Choi, 2007), la industria ósea (Hanus, 1990; Shipman y Rose, 1988), el bambú (Spennerman, 1990; West y Louys, 2007), o diferentes clases de útiles líticos (Walker, 1978; Shipman y Rose, 1983; Bello et al., 2009; Domínguez-Rodrigo et al., 2009; De Juana et al., 2010; Galán y Domínguez-Rodrigo, 2013).

El estudio de las marcas de corte en algunos yacimientos de la prehistoria ha demostrado que el descarnado de los animales se realizaba con herramientas de metal, en periodos donde las herramientas de piedra eran bastante frecuentes, como en la edad del Bronce (Greenfield, 1999, 2002, 2006a, b; Yravedra et al., 2009).

Otras investigaciones han constatado que las marcas de corte se han producido con diferentes tipos de herramientas de piedra tales como lascas simples o retocadas y bifaces, tanto experimentalmente (Walker, 1978; Bello et al., 2009; Domínguez-Rodrigo et al., 2009; De Juana et al., 2010), como en contextos arqueológicos (Shipman and Rose, 1983; Bello et al., 2009; Yravedra et al., 2011).

Estas investigaciones también pueden tener algunas limitaciones en la interpretación de esos yacimientos con gran cantidad de materias primas (e.g. los lugares con diversos tipos de sílex, cuarcitas o diferentes clases de rocas volcánicas). Los análisis experimentales han encontrado diferencias entre las marcas de corte producidas con el sílex, la cuarcita y la obsidiana, pero no han diferenciado entre diversas clases de un mismo tipo de materia prima, (e.g. diversos tipos de sílex, cuarcitas, etc.).

De este modo, cuando estudiamos un yacimiento con diversos tipos de una misma materia prima, ¿se pueden diferenciar las marcas de corte producidas con diferentes tipos de materiales líticos?, ¿pueden caracterizarse y diferenciarse las marcas realizadas con diferentes tipos de clases de una misma materia prima?

El objetivo de este estudio es evaluar si las marcas de corte resultantes del uso de diferentes sílex y diferentes cuarcitas se distinguen entre sí. En el presente trabajo se ha realizado un análisis experimental de cientos de marcas de corte producidas por cinco tipos de sílex y cinco variedades de cuarcita.

Las marcas de corte de sílex pertenecen a varias muestras de yacimientos: una de Vallecas (Madrid), dos del El Pedernoso (Cuenca), una de Manzanares (Madrid) y una de sílex blanco de Olduvai (Tanzania). Todos estos sílex son de grano fino, con tamaños de grano variables de 0.5 a 20 µm, pero con características similares a pesar de su diversa procedencia geográfica.

Las marcas de corte de cuarcita pertenecen a varias muestras de yacimientos: una de Segovia (Segovia), una de Jarama (Madrid), una de Yunquera de Henares en Guadalajara, dos del río Cares (Asturias) y una de Olduvai (Tanzania). Las cuarcitas españolas presentan cristales de cuarzo con tamaños de 177 a 250 µm, mientras que la cuarcita de Tanzania de Naibor Soit (Garganta de Olduvai) muestra cristales de cuarzo de 0.5 mm.

Para analizar estas marcas de corte se han aplicado técnicas micro-fotogramétricas y técnicas geométrico-morfométricas combinadas con distintos test estadísticos.

Los resultados demuestran que no existen diferencias significativas entre las marcas de corte producidas por distintos tipos de sílex.

En lo relativo a la cuarcita, en las pertenecientes a la Península Ibérica no existen diferencias significativas entre ellas, pero sí existen diferencias significativas con las marcas de corte realizadas con las cuarcitas de Olduvai. El tamaño de los cristales de las cuarcitas de Olduvai (0.5 mm) es mayor que el de las cuarcitas españolas (177-250 µm). Esta es la razón principal por las que se presentan diferencias estadísticamente significativas en los resultados del presente estudio.

En la comparación del conjunto global de la muestra constatamos, que las marcas de corte producidas por sílex y las producidas por cuarcita son claramente diferenciables. Sin embargo, las marcas de cortes producidas por diferentes tipos de sílex entre sí, no lo son. Sucede lo mismo con las cuarcitas de la Península Ibérica, no se pueden diferenciar las marcas producidas por los diferentes tipos de cuarcita.

Como consecuencia, podemos decir que los experimentos realizados en este estudio se pueden extrapolar a diversos yacimientos arqueológicos dentro de la Península Ibérica, siempre que contengan sílex y cuarcita entre las materias primas empleadas, ya que al menos las marcas de corte producidas por sílex y cuarcita son claramente diferenciables entre sí.

archaeometry

Flint and quartzite: Distinguishing raw material through bone cut marks

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Keywords:	Raw materials, Flint, Quartzite, Cut Marks, Micro-Morphometry, Micro-Photogrammetry.
Abstract:	Since the 1980's several experimental analyses have been able to differentiate what kind of raw material or lithic tool has generated different cut marks when used for defleshing activities. By means of these methods, metallic tool usage has been observed in contexts with an abundance of lithic tools, or even the use of hand axes has been portrayed in carcass processing in different archaeological sites. As important as this information may be, there are still other important aspects to be analysed. ¿Can cut marks produced with different types of flint be characterized and differentiated? ¿What about cut marks produced with different kinds of quartzite? The objective of this study is to evaluate whether or not these cut marks, produced by different flints and quartzites, are distinguishable from each other. Throughout this study, an experimental analysis studying numerous cut marks produced by 5 types of flint and 5 varieties of quartzite is carried out. Microphotogrametry and micromorphometry techniques have been applied to analyse these cut marks. Results show flint cut marks and quartzite cut marks can be characterized and easily distinguished one from another.

CARTA DE ACEPTACIÓN (28-Apr-2017):

Dear Mr. Maté-González:

I am writing to inform you that we are happy to accept your manuscript entitled "Flint and quartzite: Distinguishing raw material through bone cut marks" in its current form for publication in Archaeometry. The comments of the referee(s) who reviewed your manuscript are included at the foot of this letter.

Thank you for your contribution. On behalf of the Editors of Archaeometry, we look forward to your continued contributions to the Journal.

Yours sincerely,
Prof. Mark Pollard
Managing Editor, Archaeometry
mark.pollard@rlaha.ox.ac.uk

Managing Editor Comments to Author:
Managing Editor
Comments to the Author:
Dear authors, thanks for submitting the revised version of your manuscript, which can be accepted as is.
Best regards,
Ina Reiche

Referee(s)' Comments to Author:

Referee: 1

Comments to the Author
The authors have addressed my comments adequately. I have no further issues with the mansucript.

Referee: 2

Comments to the Author

I already thought that the paper was ready for publication after the first revision. This second revision of the paper takes now into account all the comments of both reviewers and is improved by the new paragraph which was added. I think it is ready to be accepted for publication and that the development of this method should be continued. It is very promising.

Manuscripts with Decisions

ACTION	STATUS	ID	TITLE	SUBMITTED	DECISIONED
	EC: Bowring, Samantha EC: Bowring, Samantha • Accept (28-Apr-2017) • Awaiting Production Checklist view decision letter	ARCH-11-0142-2016.R1	Flint and quartzite: Distinguishing raw material through bone cut marks View Submission	11-Jan-2017	28-Apr-2017
a revision has been submitted (ARCH-11-0142-2016.R1)	EC: Bowring, Samantha EC: Bowring, Samantha • Minor Revision (10-Jan-2017) • a revision has been submitted view decision letter	ARCH-11-0142-2016	Flint and quartzite: Distinguishing raw material through bone cut marks View Submission	07-Nov-2016	10-Jan-2017
a resubmission has been submitted (ARCH-11-0142-2016)	EC: Bowring, Samantha EC: Bowring, Samantha • Reject & Resubmit (29-Oct-2016) • a resubmission has been submitted view decision letter	ARCH-07-0093-2016	Flint and quartzite: Distinguishing raw material through bone cut marks View Submission	04-Aug-2016	29-Oct-2016

Flint and quartzite: Distinguishing raw material through bone cut marks

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Abstract

Since the 1980’s several experimental analyses have been able to differentiate some lithic tool types and some of their 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-morphommetric 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; Boschin 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 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, 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 (Boschin 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 andgrey to black, forming a tight interlocking network.

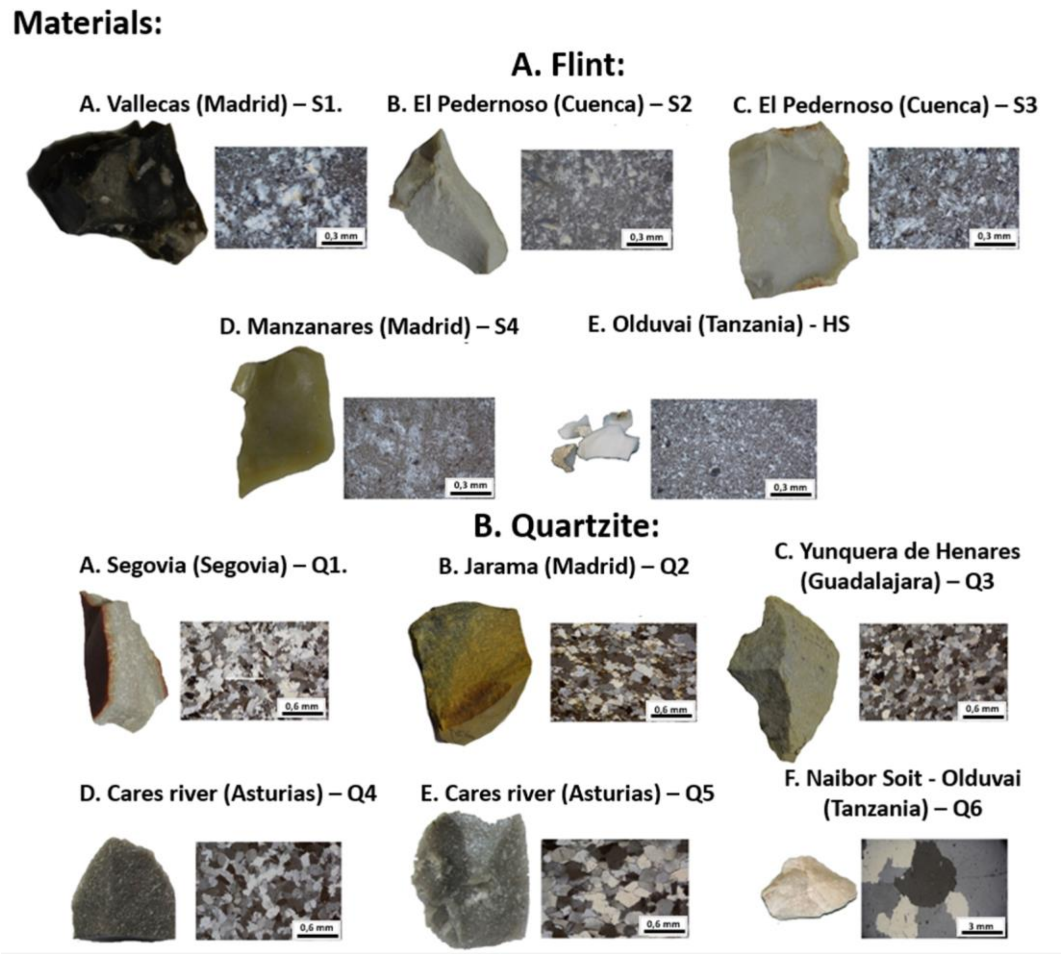


Figure 1. -> A. - Thin sections in cross-polarised light and photograph of studied flint samples. A. Vallecas flint (S1). B. El Pedernoso flint (S2). C. El Pedernoso 2 flint (S3). D. Manzanares flint (S4). E. Olduvai Gorge flint (HS). -> B. - Thin sections in cross-polarised light and photograph of studied 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.

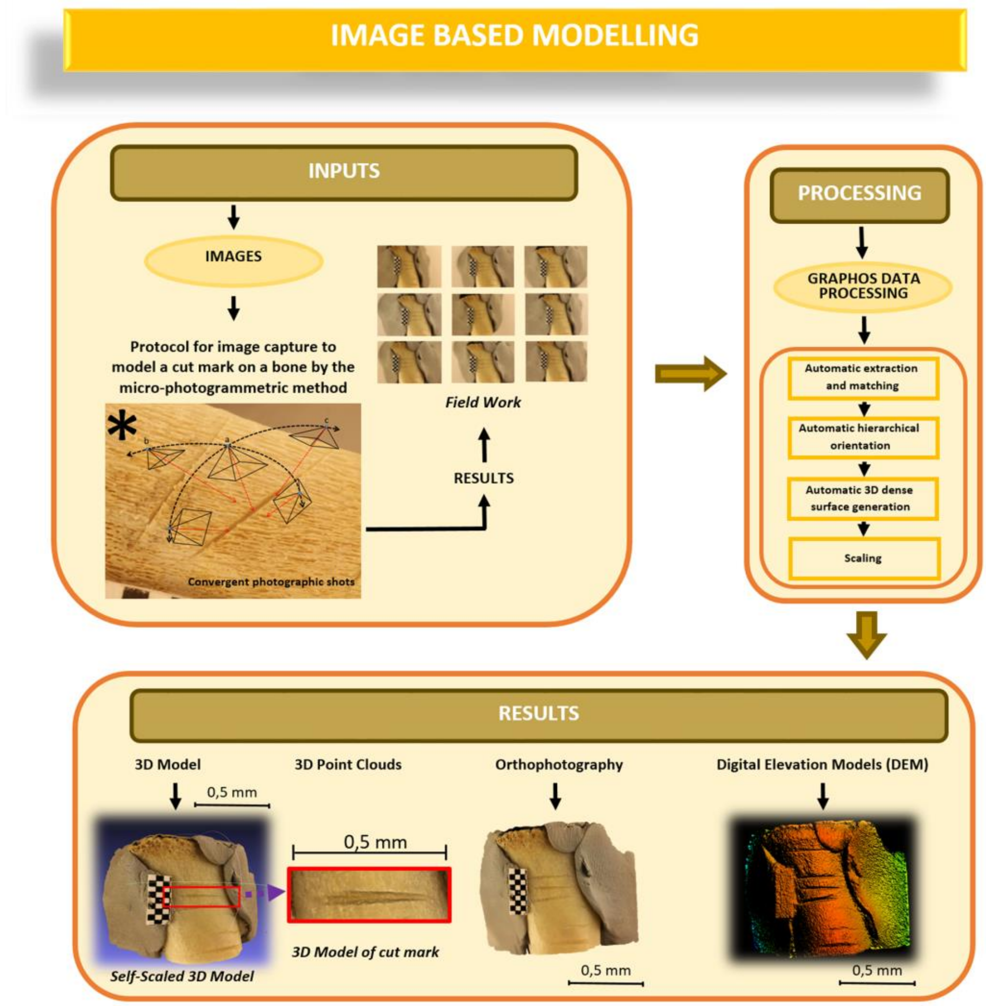


Figure 2. Workflow of the image-based modelling technique. * Protocol for image capture to model a cut mark on a bone by the micro photogrammetric method, with convergent photographic shots. A. Master and dependent images in central position B. Vertical slave images. C. Horizontal slave images.

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 mm^2; 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 thought 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).

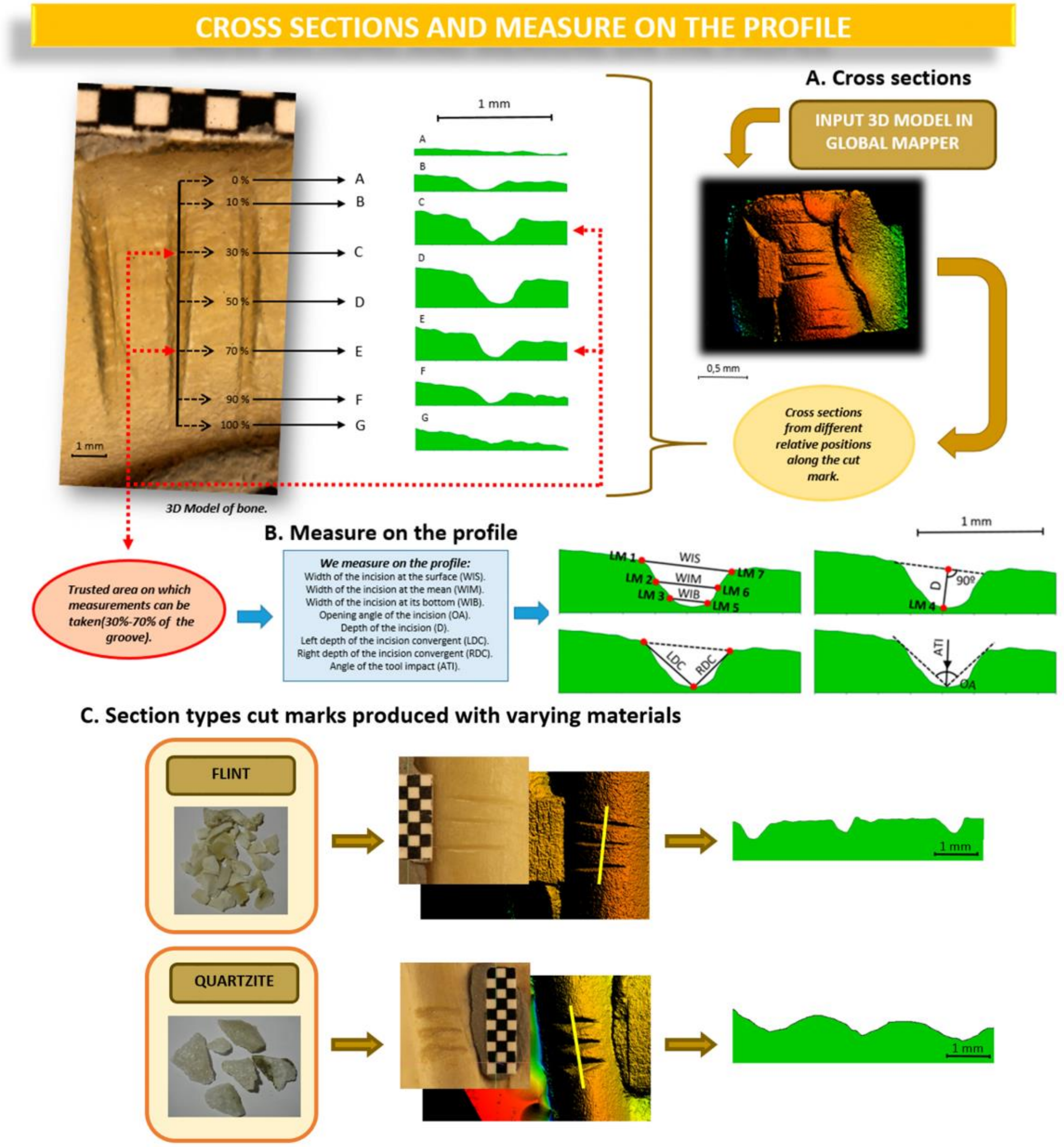


Figure 3. -> A. - Representation of the a-g sections of the cut mark regarding its length. -> B. - Location of measurements sensu Bello et al. (2013). Landmarks (LM1-7) used for the morphometric model are also represented. -> C. - Cut marks generated with a quartzite and flint flake. Detail for the V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

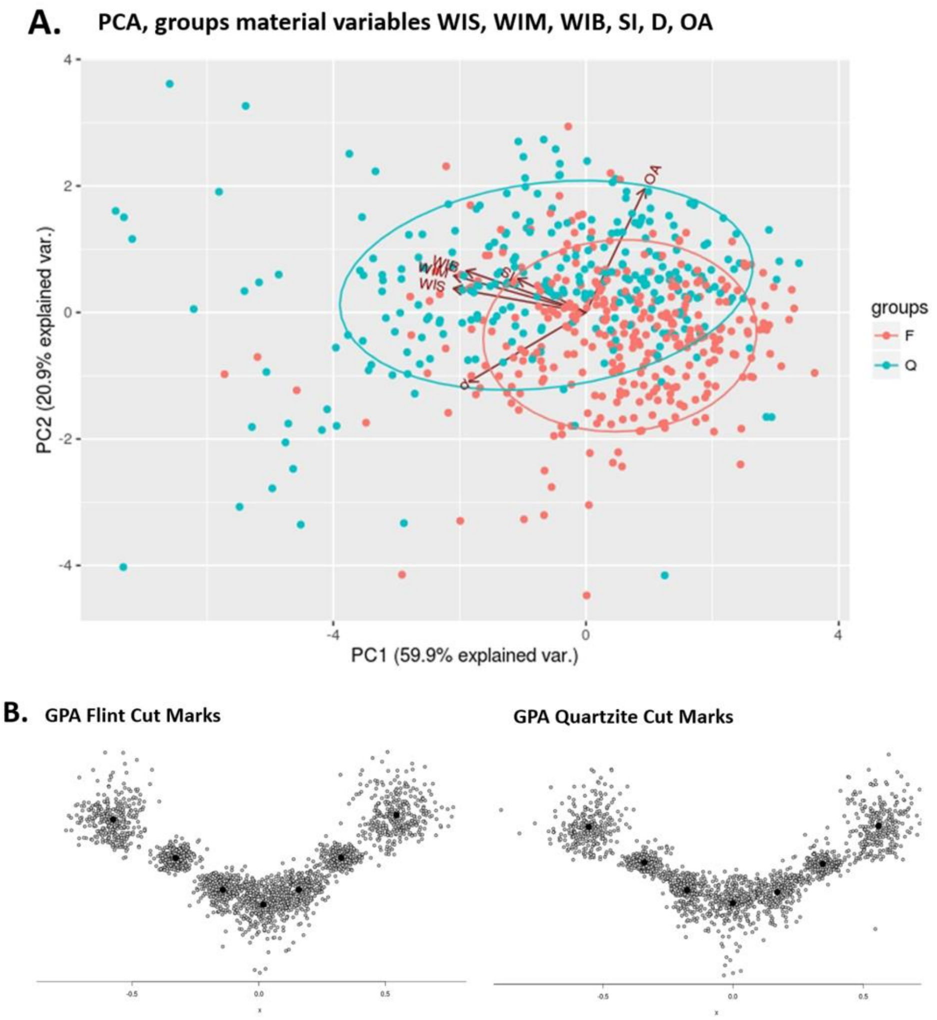
From a qualitative perspective, Figure 3.C. shows that cut marks made with flint and quartzite (regardless of the internal variance of both types of raw material) had commonly a V section, but the cut marks made with flint were narrower and deeper than the ones made with quartzite (Figure 3.A.). These 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).



C. LDA of Measurements (see fig 3.B.)

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

LDA of Morphometric analysis (see fig 3.B.)

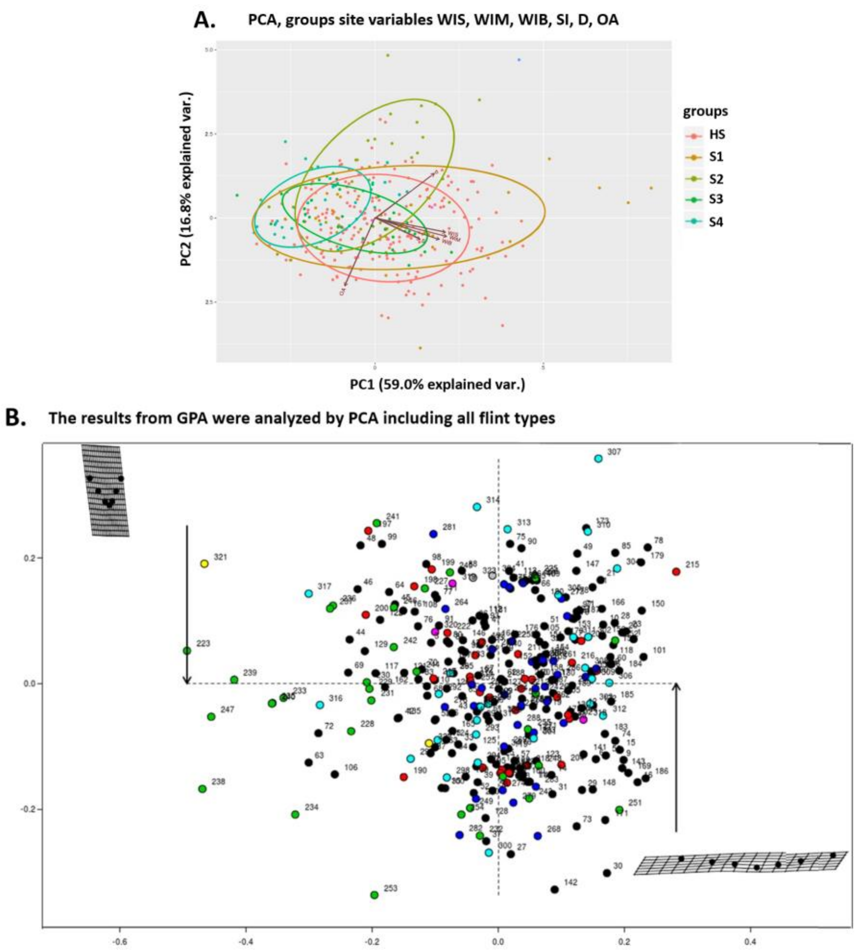
LDA	Flint	Quartzite	All cut marks
Flint	255	62	317
Quartzite	75	190	265

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.



C. LDA of Measurements (see fig 3.B.)

	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

LDA of Morphometric analysis (see fig 3.B.)

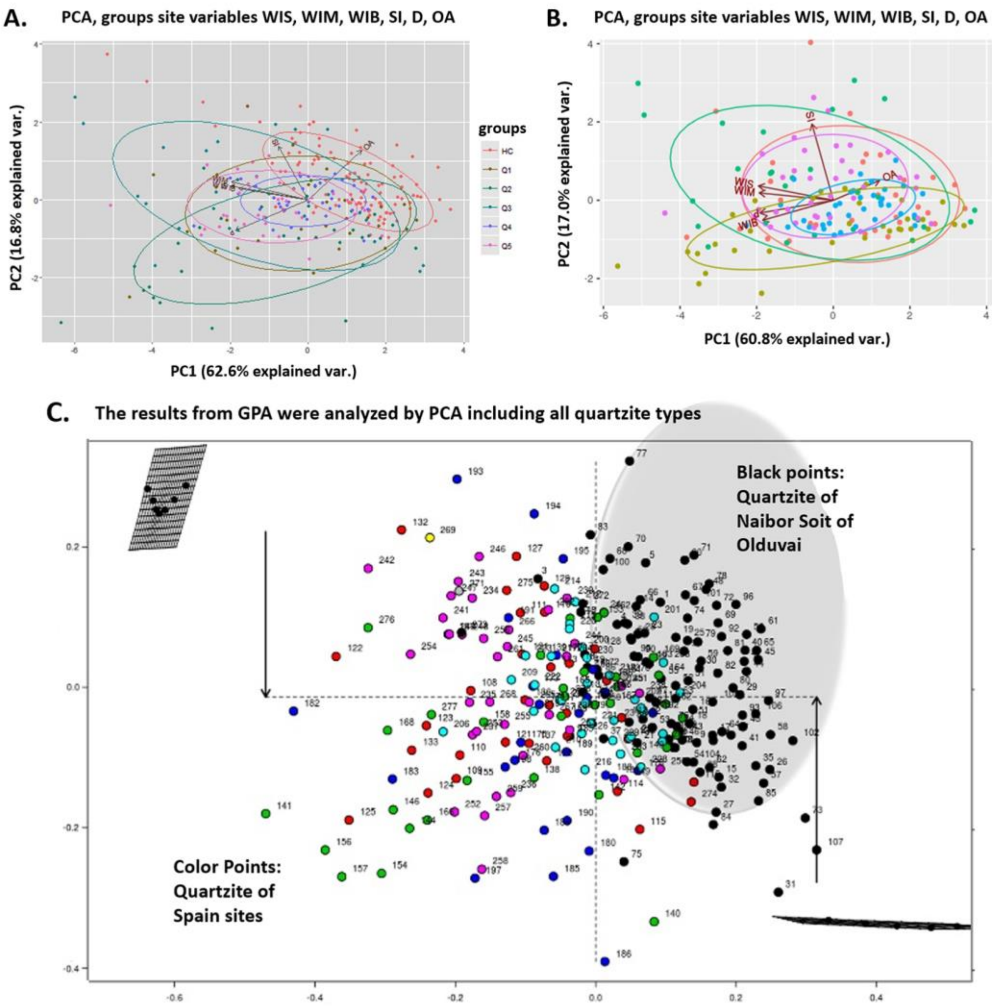
	HS	F1	F2	F3	F4
HS	172	8	2	2	5
F1	13	19	0	1	0
F2	16	0	13	1	3
F3	23	3	0	8	1
F4	13	0	4	2	8

Figure 6. -> A. - Principal 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), Yunquera 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.).



D. LDA of Measurements (see fig 3.B.)

	Q1	Q2	Q3	Q4	Q5
Q1	0	0	0	14	16
Q2	0	31	0	1	1
Q3	0	0	0	13	15
Q4	0	0	0	18	17
Q5	6	0	0	22	13

E. LDA of Morphometric analysis (see fig 3.B.)

	HC	Q1	Q2	Q3	Q4	Q5
HC	102	1	0	1	3	0
Q1	3	19	0	2	2	3
Q2	14	0	15	1	3	0
Q3	4	1	0	16	2	4
Q4	8	1	0	2	21	2
Q5	5	6	2	4	1	17

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.

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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 Prèhistoire 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 Soofware. 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. Tarriño, 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., Uribelarrea, 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 interpretating butchery marks in tropical faunal assemblages some comments asking for cauting. 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.

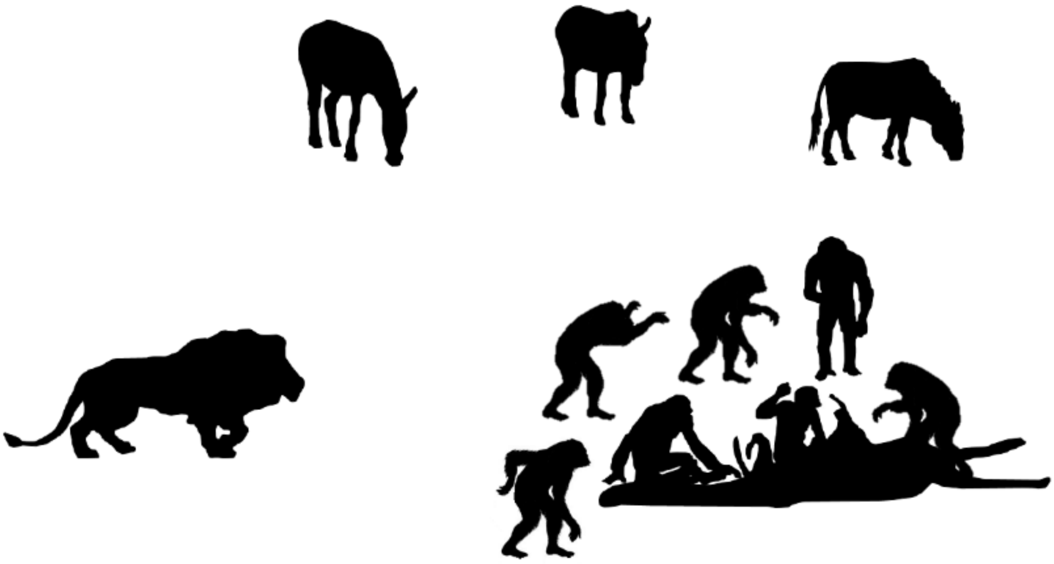
Wickham, H., 2009. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York.

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 Bronce-Iron age of the Iberian Peninsule. 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-Gonzlaez, M. A., Palomeque-González, J.; Aramendi-Picado, J., Estaca-Gómez, V., San Juan-Blázquez, M., Organista, E., González-Aguilera, D., Cobo, L.; Gidna, A., Uribelarreal 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.



Sección III: Aplicación sobre restos fósiles en yacimientos arqueológicos

En esta tercera sección llegamos al punto álgido de la presente Tesis Doctoral. Todos los trabajos realizados anteriormente, no tienen sentido si no es posible realizar una aplicación práctica que nos proporcione unos resultados satisfactorios y que nos permitan constatar que la metodología innovadora que estamos proponiendo es viable y fácilmente aplicable a un yacimiento arqueológico.

En este apartado se aplica la novedosa metodología desarrollada anteriormente, en la que se combinan técnicas micro-fotogramétricas apoyadas en la visión computacional, morfometría geométrica y test estadísticos. Esta metodología no ha sido utilizada con anterioridad en ningún contexto arqueológico, sólo ha sido aplicada a conjuntos experimentales (Maté-González et al., 2015, 2016, 2017a, b; Palomeque-González et al., 2017).

El principal objetivo que se pretende conseguir al aplicar la metodología propuesta, es determinar con qué tipo de herramienta o útil se aprovecharon los animales que aparecen en los yacimientos arqueológicos, para conocer mejor el comportamiento humano. Como veremos en esta sección, los resultados óptimos que se han conseguido al aplicar esta nueva metodología en el estudio de las marcas de corte realizadas con útiles o herramientas líticas por *Homo*, han posibilitado realizar otro tipo de estudios relacionados con procesos tafonómicos biológicos no antrópicos vinculados con la acción de los carnívoros en determinados contextos arqueológicos.

Sección III. I. Aplicación sobre el estudio de las marcas de corte

Artículo 6:

Título: **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.**

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Resumen:

El uso de técnicas micro-fotogramétricas y morfométricas geométricas como herramientas de diferenciación de las marcas de corte realizadas con diferentes materias primas sobre hueso de forma experimental ha resultado ser una metodología válida para realizar este tipo de estudios.

Este artículo se basa en la aplicación de dicha metodología a un caso práctico en el yacimiento arqueológico Bell´s Korongo (BK) (Bed II superior, Garganta de Olduvai, Tanzania). Este yacimiento es un lugar emblemático del Pleistoceno temprano donde se produce una gran acumulación faunística, incluyendo una megafauna diversa asociada a las industrias de la cuarcita y el basalto. El objetivo principal de esta investigación es conseguir, mediante esta metodología innovadora, enlazar los procesos de despiece con el tipo de materia prima utilizada para realizar dichos procesos.

Para desarrollar esta metodología, el primer paso que se ha realizado se basa en una experimentación que se ha llevado a cabo con un tipo de herramienta lítica fabricada con el mismo material que aparece en el yacimiento, la materia prima utilizada es la cuarcita y el basalto. Mediante la metodología desarrollada en anteriores artículos, se constata que existen diferencias significativas morfométricamente entre las marcas de corte realizadas con estas dos materias primas (cuarcita y basalto). Por lo tanto, los resultados del estudio experimental demuestran que existe un buen ajuste entre el tipo de materia prima y la morfología de la marca de corte, lo que nos permite aplicar con confianza este método al análisis de las marcas de corte del conjunto fósil BK.

Una vez comprobado que es posible diferenciar los dos tipos de materias primas que aparecen en el yacimiento, se ha seleccionado un conjunto de fósiles de BK que consta de un muestreo de cincuenta y ocho marcas de corte.

El resultado de comparar las marcas de corte de los restos fósiles del yacimiento arqueológico de BK con las marcas de corte realizadas de forma experimental (con las materias primas que aparecen en el yacimiento de BK), demuestra que aquellas que aparecen en los fósiles del nivel II de BK se realizaron con cuarcita. Dicha materia prima es la que predomina en todo el nivel de BK. Los arqueólogos anteriormente ya suponían estos resultados, pero con este trabajo queda probado que las marcas de corte estudiadas en los fósiles de BK se realizaron con cuarcita proveniente del Naibor Soit.

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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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BOREAS

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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

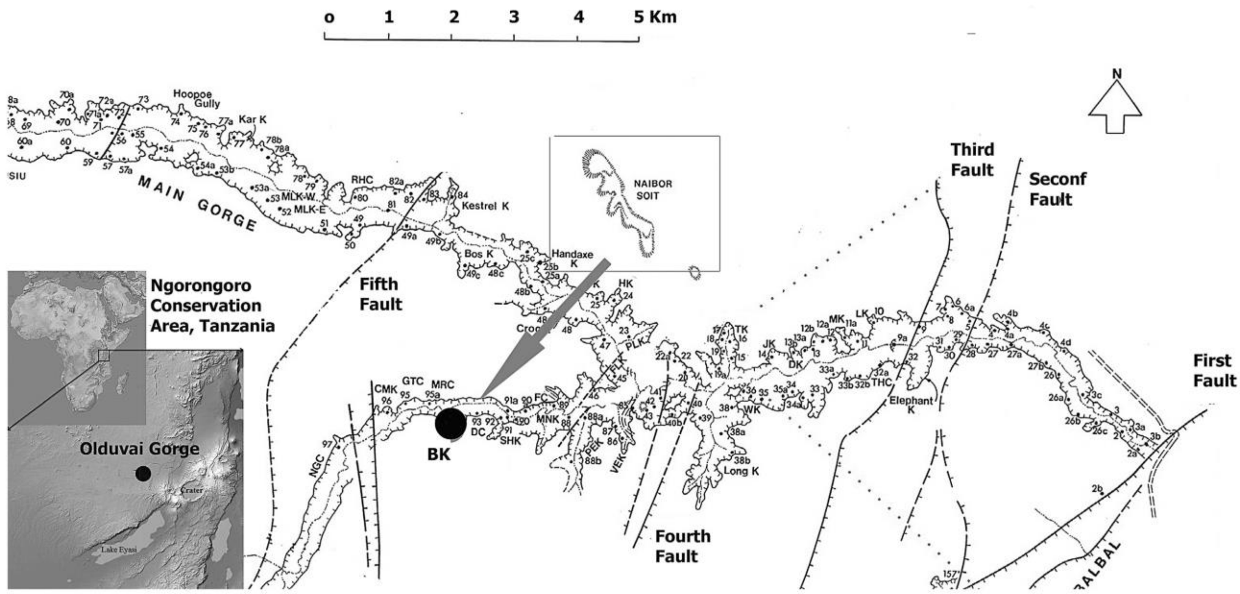

Fig. 1. Location of BK in the Olduvai Gorge and location of the Naibor Soit formation.

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

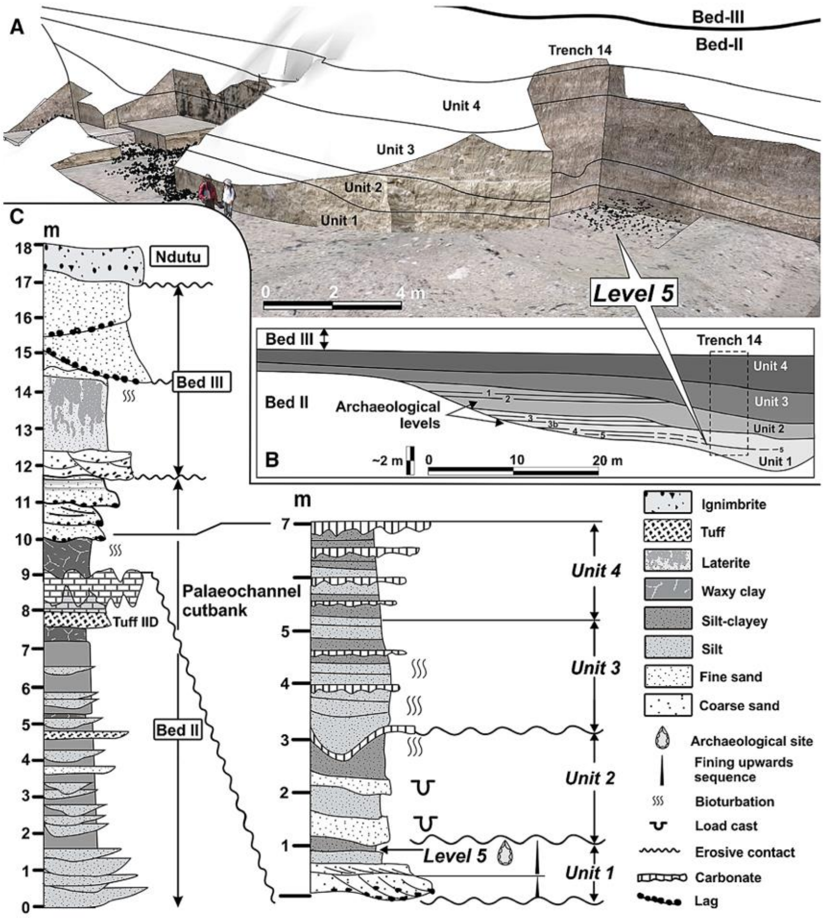

Fig. 2. A. Location of level 5 at BK. B. Detailed stratigraphical section of the four units with the different archaeological levels identified. C. Stratigraphical section across the Bed II–Bed III and Ndutu units (locality 94) in the Side Gorge. [Colour figure can be viewed at wileyonline library.com]

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

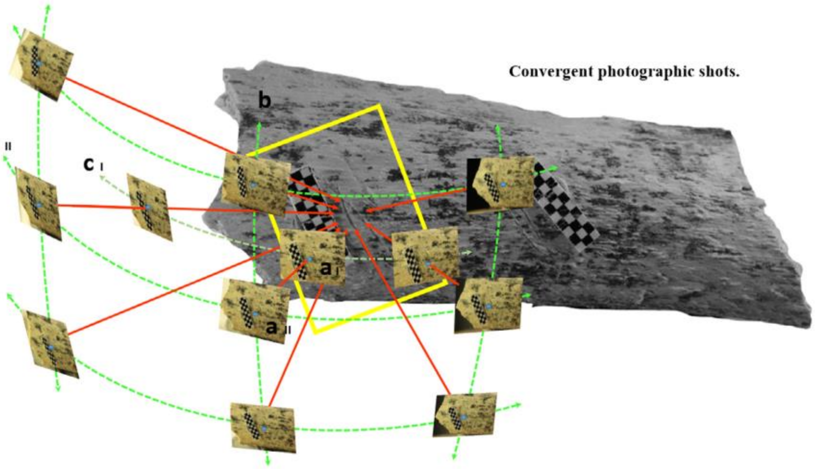

Fig. 3. Protocol for image capture to model cut marks on a bone by the micro-photogrammetric method, with convergent photographic shots. A. Master and dependent images in central position. B. Secondary images of vertical marks. C. Horizontal marks secondary images. [Colour figure can be viewed at wileyonlinelibrary.com]

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

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

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.

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.

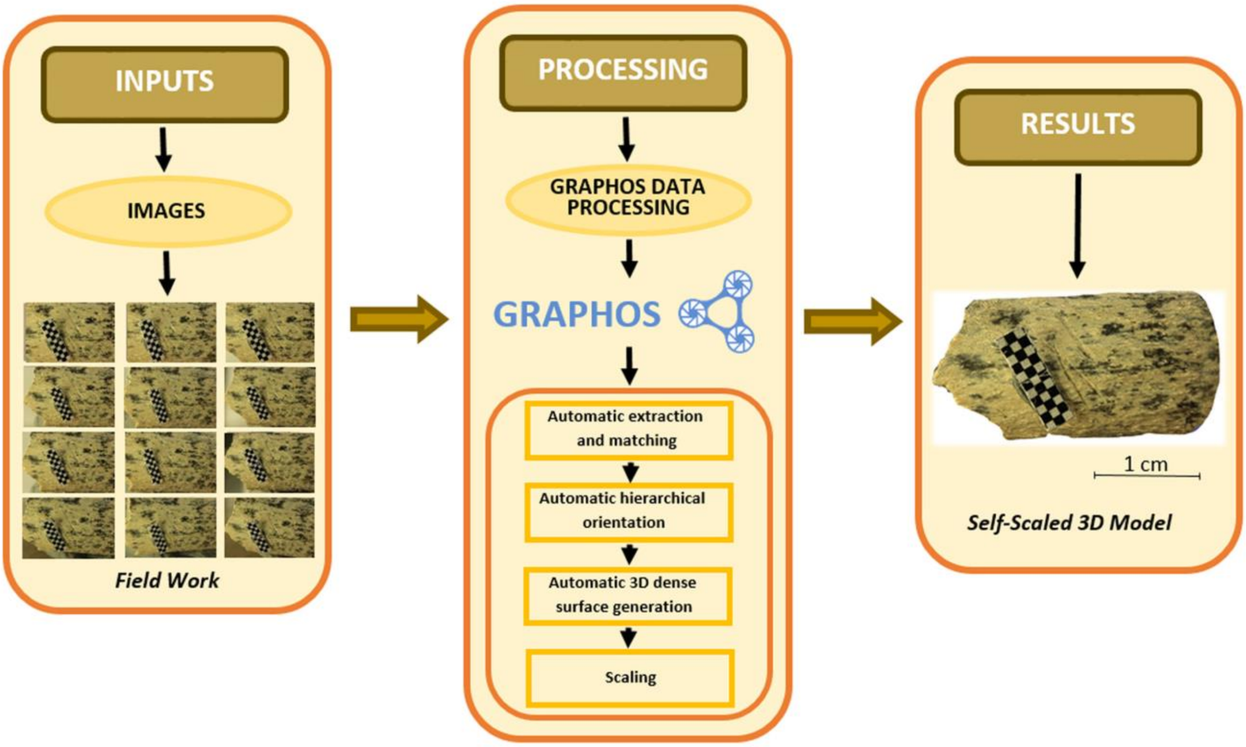

Fig. 4. Workflow of the image-based modelling technique. [Colour figure can be viewed at wileyonlinelibrary.com]

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.

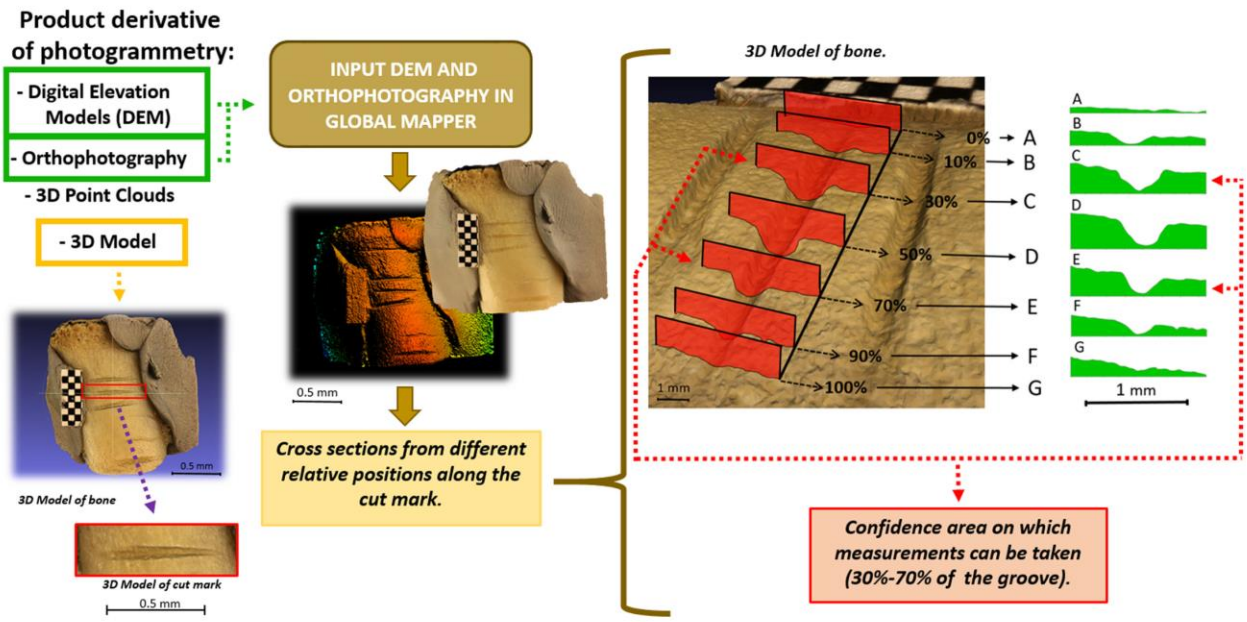

Fig. 5. Representation of the A–G sections of the cut mark regarding its length. [Colour figure can be viewed at wileyonlinelibrary.com]

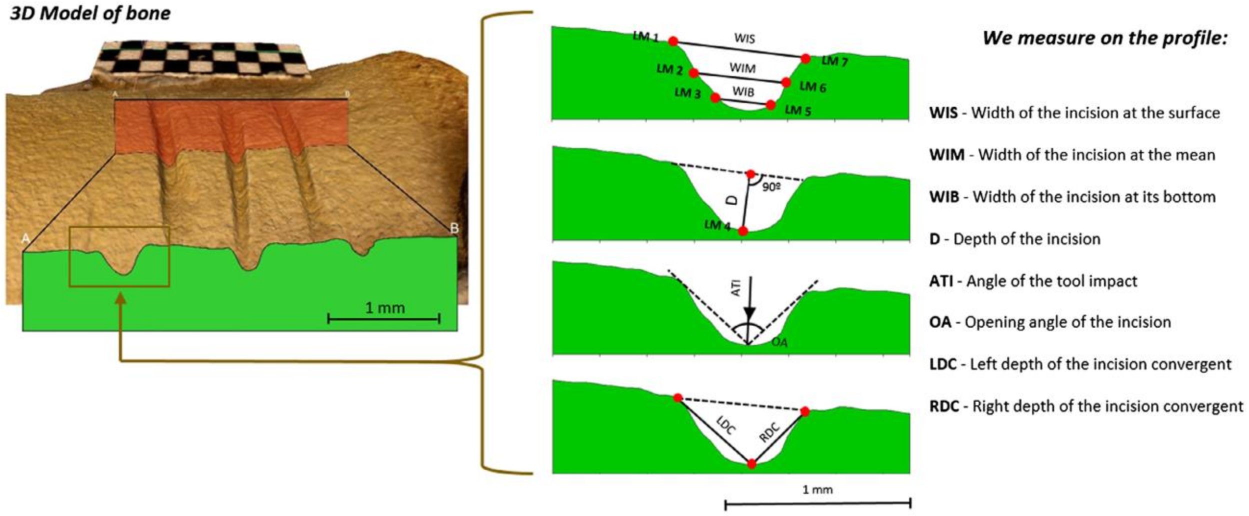

Fig. 6. Location of measurements *sensu* Bello *et al.* (2013). Semi-landmarks (LM1–7) used for the morphometric model are also represented. [Colour figure can be viewed at wileyonlinelibrary.com]

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),

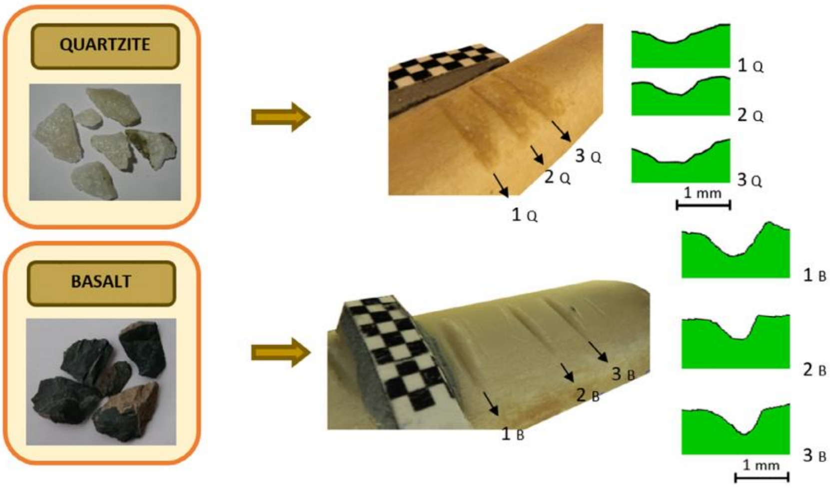

Fig. 7. Cut marks generated with a quartzite and with a basalt flake. Detail of the V sections in the three types of marks. [Colour figure can be viewed at wileyonlinelibrary.com]

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

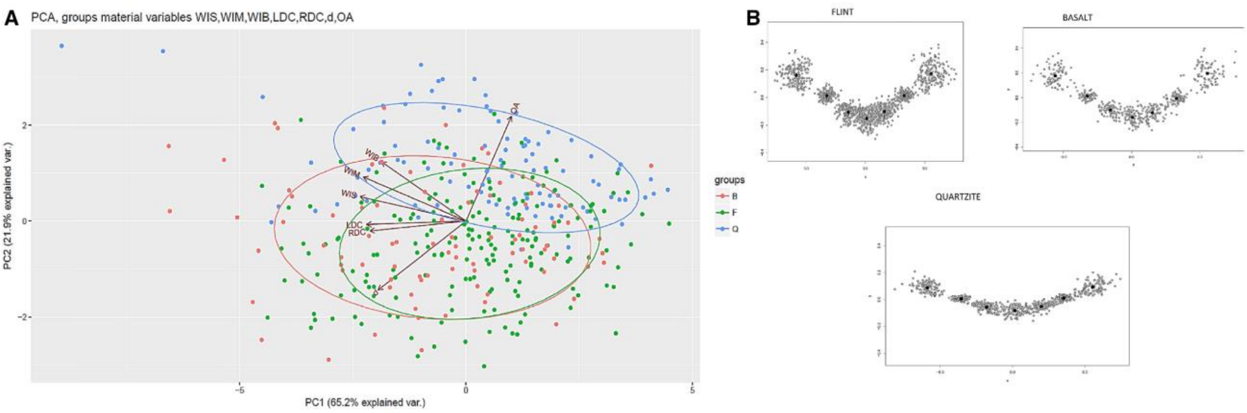

Fig. 8. A. Principal components analysis (PCA) and B. GPA with each LM centroid of cut marks produced by basalt, quartzite and flint. [Colour figure can be viewed at wileyonlinelibrary.com]

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

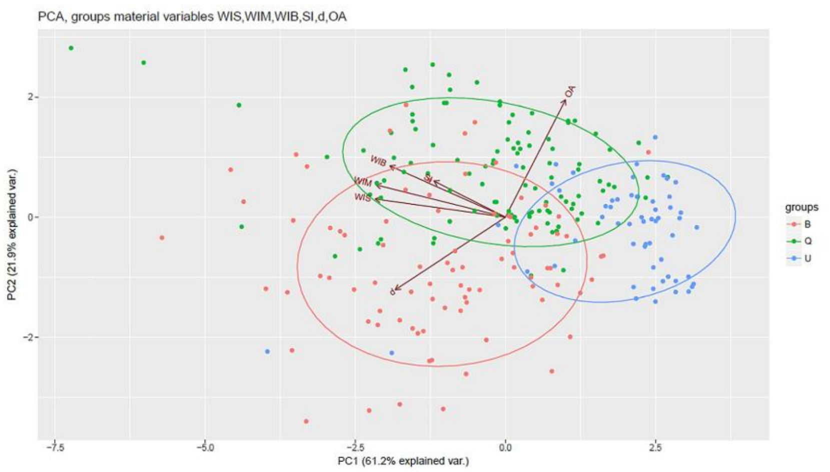

Fig. 9. Principal components analysis (PCA) of cut marks produced with quartzite (Q), basalt (B) and BK (u) tools. [Colour figure can be viewed at wileyonlinelibrary.com]

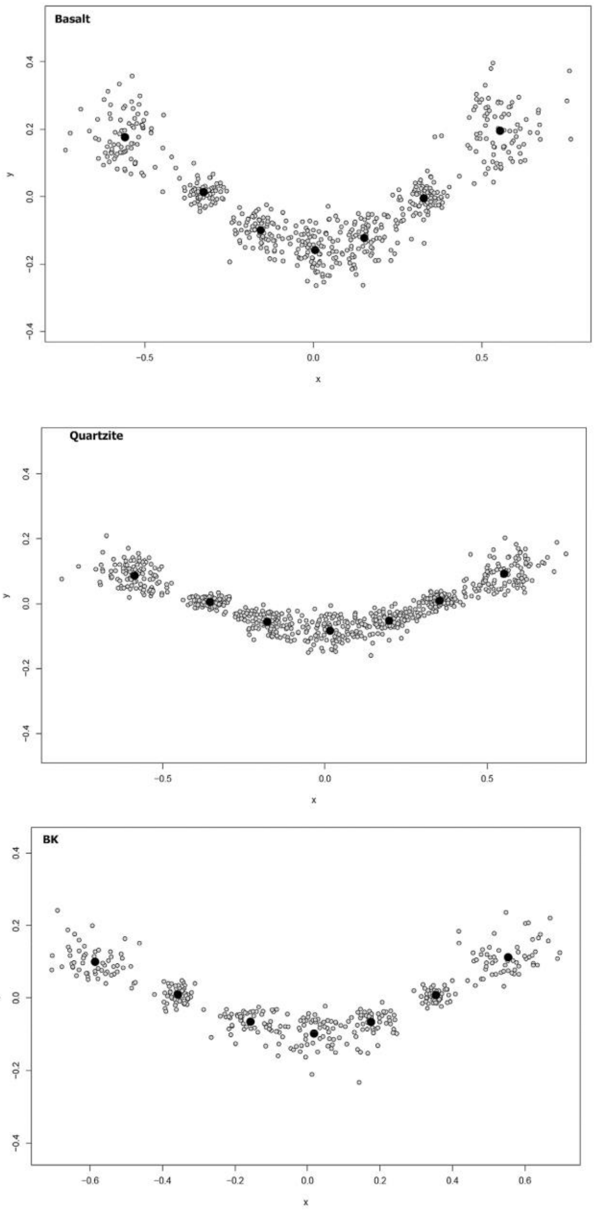

Fig. 10. Generalized Procrustes analysis (GPA) test. Silhouettes of cut marks of BK and marks produced with basalt and quartzite. Black points are the centroids associated with each semi-landmark.

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

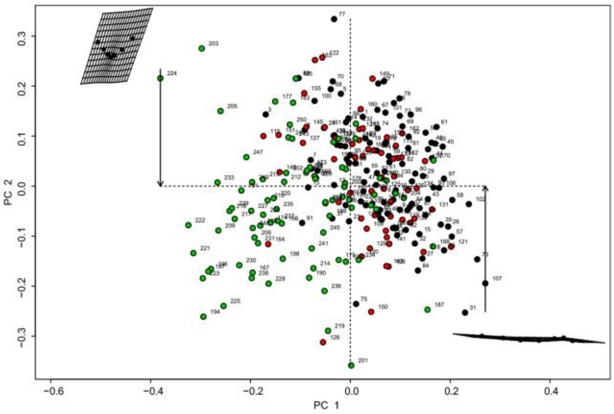

Fig. 11. Principal components analysis (PCA) of the GPA, where quartzite-related marks are in black, basalt in green and BK in red. [Colour figure can be viewed at wileyonlinelibrary.com]

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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References

Andrews, P. & Cook, J. 1985: Natural modifications to bones in a temperate setting. *Man 20*, 675–691.

Bartelink, E. J., Wiersema, J. M. & Demaree, R. S. 2001: Quantitative analysis of sharp force trauma: an application of scanning electron microscopy in forensic anthropology. *Journal of Forensic Sciences 46*, 1288–1293.

Behrensmeyer, A. K., Gordon, K. D. & Yanagi, G. T. 1986: Trampling as a cause of bone surface damage and pseudo-cutmarks. *Nature 319*, 768–771.

Bello, S. M. & Soligo, C. 2008: A new method for the quantitative analysis of cutmark micromorphology. *Journal of Archaeological Science 35*, 1542–1552.

Bello, S. M., 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. *Journal of Archaeological Science 40*, 2464–2476.

Bello, S. M., Parfitt, S. A. & Stringer, C. B. 2009: Quantitative micromorphological analyses of cut marks produced by ancient and modern handaxes. *Journal of Archaeological Science 36*, 1869–1880.

Bello, S. M., Saladié, P., Cáceres, I., Rodríguez-Hidalgo, A. & Parfitt, S. A. 2015: Upper Palaeolithic ritualistic cannibalism, Gough's Cave Somerset, UK, The human remains from head to toe. *Journal of Human Evolution 82*, 170–189.

Binford, L. R. 1981: *Bones, Ancient Men and Modern Myths.* 320 pp. Plenum Press, New York.

Binford, L. R. 1988: Fact and Fiction about the Zinjanthropus Floor, Data, Arguments, and Interpretations. *Current Anthropology 29*, 123–135.

Binford, L. R., Mills, M. G. L. & Stone, N. M. 1988: Hyena scavenging behaviour and Its Implications for the Interpretation of Faunal Assemblages from FLK 22 the Zinj floor at Olduvai Gorge. *Journal of Anthropological Archaeology 7*, 99–135.

Blumenschine, R. J. 1986: Early hominid scavenging opportunities: implications of carcass availability in the Serengeti and Ngorongoro ecosystems. *BAR International Series 283*, 163 pp.

Blumenschine, R. J. 1987: Characteristics of an early hominid scavenging niche. *Current Anthropology 28*, 383–407.

Blumenschine, R. J. 1988: An experimental model of the timing of hominid and carnivore influence on archaeological bone assemblages. *Journal of Archaeological Science 15*, 483–502.

Blumenschine, R. J. 1989: A landscape taphonomic model of the scale of prehistoric scavenging opportunities. *Journal of Human Evolution 18*, 345–371.

Blumenschine, R. J. 1991: Hominid carnivore and foraging strategies, and the socio-economic function of early archaeological sites. *Philosophical Transactions of the Royal Society London 334*, 211–221.

Blumenschine, R. J. 1995: Percussion marks, tooth marks, and experimental determinations of the timing of hominid and carnivore access to long bones at FLK Zinjanthropus, Olduvai Gorge, Tanzania. *Journal of Human Evolution 29*, 21–51.

Blumenschine, R. J. & Selvaggio, M. M. 1988: Percussion marks on bone surfaces as a new diagnostic of hominid behaviour. *Nature 333*, 763–765.

Blumenschine, R. J., Cavallo, J. A. & Capaldo, R. J. 1994: Competition from carcases and early hominid behavioural ecology, a case study and conceptual framework. *Journal of Human Evolution 27*, 94–214.

Blumenschine, R. J., Marean, C. & Capaldo, S. 1996: Blind test of inter-analyst correspondence and accuracy in the identification of cut marks. Percussion marks and carnivore tooth marks on bone surface. *Journal of Archaeological Science 23*, 493–505.

Blumenschine, R. J., Prassack, K., Kreger, C. D. & Pante, M. 2007: Carnivore tooth marks, microbial bioerosion and the invalidation of Domínguez-Rodrigo, M. & Barba's, R. 2006 test of Oldowan hominid scavenging behavior. *Journal of Human Evolution 53*, 420–426.

Blumenschine, R. J., Stanistreet, I. G., Njau, J. K., Bamford, M. K., Masao, F. T., Albert, R. M., Stollhofen, H., Andrews, P., Prassack, K. A., McHenry, L. J., Fernández-Jalvo, Y., Camilli, E. L. & Ebert, J. L. 2012: Environments and hominin activities across the FLK Peninsula during Zinjanthropus times 1.84 Ma, Olduvai Gorge, Tanzania. *Journal of Human Evolution 63*, 364–383.

Boschin, F. & Crezzini, J. 2012: Morphometrical analysis on cut marks using a 3D digital microscope. *International Journal of Osteoarchaeology 22*, 549–562.

Bunn, H. T. 1981: Archaeological evidence for meat-eating by Plio-Pleistocene hominids from Koobi Fora and Olduvai Gorge. *Nature 291*, 574–577.

Bunn, H. T. 1982: *Meat-Eating and Human Evolution, Studies on the Diet and Subsistence Patterns of Plio- Pleistocene Hominids in East Africa.* Ph.D. thesis, University of California Berkeley, 384 pp.

Bunn, H. T. 1986: Patterns of skeletal representation and hominid subsistence activities at Olduvai Gorge, Tanzania, and Koobi Fora, Kenya. *Journal of Human Evolution 15*, 673–690.

Bunn, H. T. 2007: Meat made us human. *In* Ungar, P. S. (ed): *Evolution of the Human Diet*, 191–211. Oxford University Press, Oxford.

Bunn, H. T. & Kroll, E. M. 1986: Systematic butchery by Plio/Pleistocene hominids at Olduvai Gorge, Tanzania. *Current Anthropology 27*, 431–452.

Bunn, H. T. & Pickering, T. R. 2010: Bovid mortality profiles in paleoecological context falsify hypotheses of endurance running-hunting and passive scavenging by early Pleistocene hominins. *Quaternary Research 74*, 395–404.

Capaldo, S. D. 1997: Experimental determinations of carcass processing by Plio-Pleistocene hominids and carnivores at FLK 22 Zinjanthropus, Olduvai Gorge, Tanzania. *Journal of Human Evolution 33*, 555–597.

Capaldo, S. D. 1998: Simulating the formation of dual-patterned archeofaunal assemblages with experimental control samples. *Journal Archaeological Science 25*, 311–330.

Capaldo, S. D. & Blumenschine, R. J. 1994: A quantitative diagnosis of notches made by hammerstone percussion and carnivore gnawing on bovid long bones. *American Antiquity 59*, 724–748.

Cavallo, J. A. & Blumenschine, R. J. 1989: Tree-stored leopard kills, expanding the hominid scavenging niche. *Journal of Human Evolution 18*, 393–399.

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., Dominguez-Rodrigo, M., Mabulla, A. Z. P. & Barba, R. 2009: Where Olduvai hominins making butchering tools or battering tools? Analysis of a recently excavated lithic assemblage from BK Bed II, Olduvai Gorge, Tanzania. *Journal of Anthropological Archaeology 28*, 274–289.

Domínguez-Rodrigo, M. 1994: *El origen del comportamiento humano.* 324 pp. Ediciones Tipo, Madrid.

Domínguez-Rodrigo, M. 1996: A landscape study of bone conservation in the Galana and Kulalu Kenya ecosystem. *Origini 20*, 17–38.

Domínguez-Rodrigo, M. 1997: Meat eating by early hominids at FLK Zinj 22 Site, Olduvay Gorge Tanzania, An experimental a roach using cut-mark data. *Journal of Human Evolution 33*, 669–690.

Domínguez-Rodrigo, M. 1999: Flesh availability and bone modifications in carcasses consumed by lions, palaeoecological relevance in hominid foraging patterns. *Palaeogeography, Paleoclimatology, Paleoecology 149*, 373–388.

Domínguez-Rodrigo, M. 2001: A study of carnivore competition in riparian and open habitats of modern savannas and its implications for hominid behavioural modelling. *Journal of Human Evolution 40*, 77–98.

Domínguez-Rodrigo, M. 2002: Hunting and scavenging by early humans: the state of debate. *Journal of World Archaeology 16*, 1–54.

Domínguez-Rodrigo, M. & Barba, R. 2006: New estimates of tooth marks and percussion marks from FLK Zinj, Olduvai Gorge Tanzania, the carnivore-hominid carnivore hypothesis falsified. *Journal of Human Evolution 50*, 170–194.

Domínguez-Rodrigo, M., Barba, R. & Egeland, C. P. 2007: *Deconstructing Olduvai*. 307 pp. Springer, New York.

Domínguez-Rodrigo, M., Bunn, H. T., Mabulla, A. Z. P., Ashley, G. M., Diez-Martin, F., Barboni, D., Prendergast, M. E., Yravedra, J., Barba, R., Sánchez, A., Baquedano, E. & Pickering, T. R. 2010a: New excavations at the FLK Zinjanthropus site and its surrounding landscape and its behavioural implications. *Quaternary Research 74*, 315–332.

Domínguez-Rodrigo, M., Bunn, H. T., Mabulla, A. Z. P., Baquedano, E., Uribelarrea, D., Pérez-González, A., Gidna, A., Yravedra, J., Diez-Martín, F., Barba, R., Arriaza, C., Egeland, C. P., Organista, E. & Ansón, M. 2014b: On meat eating and human evolution, a taphonomic analysis of BK4b, Upper Bed II, Olduvai Gorge, Tanzania and its bearing on hominin megafaunal consumption. *Quaternary International 322–323*, 129–152.

Domínguez-Rodrigo, M., Bunn, H. T. & Yravedra, J. 2014a: A critical reevaluation of bone surface modification models for inferring fossil hominin and carnivore interactions through a multivariate approach, application to the FLK Zinj archaeofaunal assemblage Olduvai Gorge; Tanzania. *Quaternary International 322–323*, 32–43.

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

Domínguez-Rodrigo, M., Mabulla, A., Bunn, H. T., Barba, R., Diez-Martin, F., Egeland, C. P., Espilez, E., Egeland, A., Yravedra, J. & Sánchez, P. 2009a: Unraveling hominin behavior at another anthropogenic site from Olduvai Gorge Tanzania, new archaeological and taphonomic research at BK, Upper Bed II. *Journal of Human Evolution 57*, 260–283.

Domínguez-Rodrigo, M., Pickering, T. R., Almecija, S., Heaton, J. L., Baquedano, E., Mabulla, A. Z. P. & Uribelarrea, D. 2015: Earliest modern human-like hand bone from a new >1.84-million-year-old site at Olduvai in Tanzania. *Nature Communications 6*, 7987, doi: 10.1038/ncomms8987.

Domínguez-Rodrigo, M., Pickering, T. R. & Bunn, H. T. 2010b: Configurational approach to identifying the earliest hominin butchers. *Proceedings of the National Academy of Sciences of the United States of America 107*, 20929–20934.

Domínguez-Rodrigo, M., Pickering, T. R. & Bunn, H. T. 2011: Reply to McPherron et al. Doubting Dikika is about data, not paradigms. *Proceedings of the National Academy of Sciences of the United States of America 108*, p. 117.

Domínguez-Rodrigo, M., Pickering, T. R. & Bunn, H. T. 2012b: Experimental study of cut marks made with rocks unmodified by human flaking and its bearing on claims of 3.4-million-year-old butchery evidence from Dikika, Ethiopia. *Journal of Archaeological Science 39*, 205–214.

Domínguez-Rodrigo, M., Pickering, T. R., Diez-Martín, F., Mabulla, A., Musiba, C., Trancho, G., Baquedano, E., Bunn, H., Barboni, D., Sanntonja, M., Uribelarrea, D., Ashley, G., Martínez-Ávila, M. S., Barba, R., Gidna, A., Yravedra, J. & Arriza, C. 2012a: Earliest porotic hyperostosis on a 1.5-million-year-old hominin, Olduvai Gorge, Tanzania. *PLoS ONE 7*(10), e46414, doi: 10.1371/journal.pone.0046414.

Domínguez-Rodrigo, M., Pickering, T. R., Mabulla, A., Mark, D. F., Musiba, C., Bunn, H. T., Baquedano, E., Uribelarrea, D., Smith, V., Díez-Martín, F., Pérez-González, A., Sánchez, P., Santonja, M., Barboni, D., Gidna, A., Ashley, G., Yravedra, J., Heaton, J. L. & Arriaza, C. 2013: First partial skeleton of a 1.34-million-year-old *Paranthropus boisei* from Bed II, Olduvai Gorge, Tanzania. *PLoS ONE 8*(12), e80347, doi: 10.1371/journal.pone.0080347.

Domínguez-Rodrigo, M., Pickering, T. P., Semaw, S. & Rogers, M. J. 2005: Cutmarked bones from Pliocene archaeological sites at Gona, Afar, Etiopía: Implications for the function of the world's oldest stone tools. *Journal of Human Evolution 48*, 109–121.

Egeland, C. P. 2008: Patterns of early hominid site use at Olduvai Gorge. *Mitteilungen der Gesellschaft für Urgeschichte 17*, 9–37.

Egeland, C. P. & Domínguez-Rodrigo, M. 2008: Taphonomic perspectives on hominid site use and foraging strategies during Bed II times at Olduvai Gorge, Tanzania. *Journal of Human Evolution 55*, 1031–1052.

Fiorillo, A. R.1989: An experimental study of trampling: implications for the fossil record. *In* Bonnichsen, R. & Sorg, M. H. (eds.): *Bone Modification*, 61–72. Center for the Study of Early Man, Orono, Maine.

Fisher, J. W. 1995: Bone surface modifications in zooarchaeology. *Journal of Archaeological Method and Theory 2*, 7–68.

Fraser, C. 1980: Multiple focal setting self-calibration of close-range metric cameras. *Photogrammetric Engineering and Remote Sensing 46*, 1161–1171.

Giacobini, G. & Patou Mathis, M. 2002: *Fiche rappels taphonomiques. Industrie de l'os préhistorique. Cahier X. Retoucheurs, compresseurs, percuteurs.* 21 pp. Editions Société Préhistorique Française, Paris.

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 30.04.2014.

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 on Development of an all-purpose free photogrammetric tool, 12 to 19 July 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. CATCON7-ISPRS Congress, 12 to 19 July 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. 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. *Journal of Israel Prehistoric Society 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.

Hay, R. 1976: *Geology of the Olduvai Gorge*. 220 pp. University of California Press, Berkeley.

Isaac, G. L. 1981: Stone Age visiting cards, approaches to the study of early land use patterns. *In* Hodder I., Isaac G. L. & Hammond N. (eds.): *Pattern of the Past. Studies in Honour of David Clarke*, 131–155. Cambridge University Press, Cambridge.

Kaiser, T. M. & Katterwe, H. 2001: The application of 3D-microprofilometry as a tool in the surface diagnosis of fossil and sub-fossil vertebrate hard tissue. An example from the Pliocene Upper Laetoli Beds, Tanzania. *International Journal of Osteoarchaeology 11*, 350–356.

Kyara, O. A. 1999: *Lithic raw materials and their implications on assemblage variation and hominid behavior during Bed II, Olduvai Gorge, Tanzania*. Ph.D. thesis, University of Rutgers, 438 pp.

Leakey, L. S. B. 1931: *The Stone Age Cultures of Kenya Colony.* 288 pp. Cambridge University Press, London.

Leakey, L. S. B. 1936: *Stone Age Africa. An outline of Prehistory in Africa*. 218 pp. Oxford University Press, London.

Leakey, L. S. B. 1951: *Olduvai Gorge*, 1951–1961, *Volume 1*. 118 pp. Cambridge University Press, Cambridge.

Leakey, L. S. B. 1959: A new fossil skull from Olduvai. *Nature 184*, 491–493.

Leakey, L. S. B. 1960: Recent discoveries at Olduvai Gorge. *Nature 188*, 1050–1052.

Leakey, M. D. 1971: *Olduvai Gorge., Volume 3. Excavations in Beds I and II, 1960-1963*. 328 pp. Cambridge University Press, Cambridge.

Leakey, L. S. B. & Leakey, M. D. 1964: Recent discoveries of fossil hominids in Tanganyika, at Olduvai and Near Lake Natron. *Nature 202*, 5–7.

Leakey, L. S. B., Tobias, P. V. & Napier, J. R. 1964: A new species of the genus *Homo* from Olduvai Gorge. *Nature 202*, 8–10.

Luhmann, T., Robson, S., Kyle, S. & Boehm, J. 2013: *Close-range Photogrammetry and 3D Imaging*. 1012 pp. Walter De Gruyter, Berlin.

Maté González, M. A., Palomeque-González, J. F., 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 and Anthropological Sciences (2016)*, doi: 10.1007/ s12520-016-0401-5.

Maté González, M. A., Yravedra, J., González-Aguilera, D., Palomeque-González, J. F. & Domínguez-Rodrigo, M. 2015: Micro-photogrammetric characterization of cut marks on bones. *Journal of Archaeological Science 62*, 128–142.

McPherron, S. P., Alemseged, Z., Marean, C. W., Wynn, J. G., Reed, D., Geraads, D., Bobe, R. & Bearat, H. A. 2010: Evidence for stone-tool-assisted consumption of animal tissues before 3.39 million years ago at Dikika, Ethiopia. *Nature 466*, 857–860.

McPherron, S. P., Alemseged, Z., Marean, C., Wynn, J. G., Reed, D., Geraads, D., Bobe, R. & Bearat, H. 2011: Tool-marked bones from before the Oldowan change the paradigm. *Proceedings of the National Academy of Sciences of the United States of America 108*, p. 116.

Monahan, C. M. 1996: New zooarchaeological data from Bed II, Olduvai Gorge, Tanzania, Implications for hominid behavior in the early Pleistocene. *Journal of Human Evolution 31*, 93–128.

Olsen, S. L. 1988: The identification of stone and metal tool marks on bone artefact. *BAR International Series 452*, 337–360.

Olsen, S. L. & Shipman, P. 1988: Surface modification on bone, trampling vs butchery. *Journal of Archaeological Science 15*, 535–553.

Organista, E., Domínguez-Rodrigo, M., Egeland, C., Uribelarrea, D., Mabulla, A. & Baquedano, E. 2015: Did Homo erectus kill a Pelorovis herd at BK Olduvai Gorge? A taphonomic study of BK5. *Archaeological and Anthropological Sciences 8*, 601, doi:10. 1007/s12520-015-0241-8.

Pante, M. C., Blumenschine, R. J., Capaldo, S. D. & Scott, R. S. 2012: Validation of bone surface modification models for inferring hominin and carnivore feeding interactions, with reapplication to FLK 22, Olduvai Gorge, Tanzania. *Journal of Human Evolution 63*, 395–407.

Pante, M. C., Muttat, M., Keevil, T. L., Blumenschine, R. J., Njau, J. & Merritt, S. R. 2017: A new high-resolution 3-D quantitative method for identifying bone surface modifications with implications for the Early Stone Age archaeological record. *Journal of Human Evolution 102*, 1–11.

Peters, C. R. & Blumenschine, R. J. 1995: Landscape perspectives on possible land use patterns for Early Pleistocene hominids in the Olduvai Basin, Tanzania. *Journal of Human Evolution 29*, 321–362.

Potts, R. 1988: *Early Hominid Activities at Olduvai*. 396 pp. Aldine and Gruyter, New York.

Potts, R. & Shipman, P. 1981: Cutmarks made by stone tools on bones from Olduvai Gorge, Tanzania. *Nature 291*, 577–580.

Selvaggio, M. M. 1994: Carnivore tooth marks and stone tool butchery marks on scavenges bones, Archaeological implications. *Journal of Human Evolution 27*, 215–228.

Selvaggio, M. M. 1998: Evidence for a three-stage sequence of hominid and carnivore involvement with long bones at FLK Zinjanthropus, Olduvai Gorge, Tanzania. *Journal of Archaeological Science 25*, 191–202.

Sherratt, E. 2014: *Quick Guide to Geomorphology 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 Anthropological Archaeology 2*, 57–98.

Spennerman, D. H. R. 1990: Don't forget the bamboo on recognising and interpreting butchery marks in tropical faunal assemblages some comments asking for cauting. *In* Solomon S., Davidson I. & Watson D. (eds.): *Problems Solving Taphonomy,* 80–101. *Tempus 2,* University of Queensland Anthropology Museum, Saint Lucia.

Tappen, M. 1992: *Taphonomy of a central African savanna: Natural bone deposition in Parc National des Virunga, Zaire*. Ph.D. thesis, Harvard University, 366 pp.

Tappen, M. 1995: Savanna ecology and natural bone deposition: implications for early hominid site formation, hunting, and scavenging. *Current Anthropology 36*, 223–260.

Thompson, J. C., McPherron, S. P., Bobe, R. E., Reed, D. E., Barr, W. A., Wynn, J., Marean, C. V., Geraads, D. & Alemseged, Z. 2015: Taphonomy of fossils from the hominin-bearing deposits at Dikika, Ethiopia. *Journal of Human Evolution 86*, 112–135.

Walker, P. L. 1978: Butchering and stone tool function. *American Antiquity 43*, 710–715.

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., Domínguez-Rodrigo, M., Santonja, M., Rubio-Jara, S., Panera, J., Pérez-González, A., Uribelarrea, D., Egeland, C., Mabulla, A. & Baquedano, E. 2016: The large mammal palimpsest from TK Thiongo korongo, Bed II Olduvai Gorge, Tanzania. *Quaternary International 417*, 3–15.

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.

Artículo 7:

Título: **FLK West (Lower Bed II, Olduvai-Gorge, Tanzania): A new early Acheulean site with evidence for human exploitation of fauna.**

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Resumen:

Este artículo se presenta un estudio tafonómico detallado del conjunto faunístico de FLK West (Frida Leakey Korongo) (Garganta de Olduvai, Tanzania), un yacimiento con un componente Achelense que data de 1.7 millones de años. La muestra de la fauna analizada se distribuye en diferentes niveles arqueológicos y se asocia con una acumulación lítica muy importante que incluye varias lascas de gran formato y hachas de mano como elementos más característicos del complejo Achelense. Paleoecológicamente, la fauna se caracteriza por especies que habitan ambientes abiertos, similares a los encontrados en otros lugares como en el Bed II y al final en el Bed I de Olduvai Gorge. Tafonómicamente la fauna presenta varias evidencias de actividad antrópica, de este modo se han identificado huesos con marcas de corte y de percusión asociadas a actividades de descarnado y consumo de médula.

Los análisis fotogramétricos y morfométricos de las marcas de corte realizados, constatan que estas se llevaron a cabo con lascas simples de cuarcita en lugar de con bifaces o hachas de mano. Anteriormente a este trabajo se especulaba sobre la funcionalidad de los bifaces en los contextos del Pleistoceno inferior africano, ya que raras veces aparecen asociados a fauna, sin embargo en este caso si lo están. Los resultados obtenidos sugieren que los bifaces no se utilizaron en el procesado de las carcasas, teniendo por tanto otra utilidad como la explotación de recursos vegetales.

La interacción con los carnívoros está registrada a través de las marcas de diente que se han observado en algunos huesos, lo que refleja la competitividad entre humanos y carnívoros por los mismos nichos ecológicos, algo con lo que tuvieron que lidiar los homínidos del Pleistoceno inferior.

Finalmente desde una perspectiva paleoecológica la fauna sugiere la proliferación de espacios abiertos reproduciendo algunas de las observaciones que se han realizado en otros lugares del Bed II.

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FLK West (Lower Bed II, Olduvai Gorge, Tanzania): a new early Acheulean site with evidence for human exploitation of fauna

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BOREAS

Yravedra, J., Diez-Martín, F., Egeland, C. P., Maté-González, M. Á., Palomeque-González, J. F., Arriaza, M. C., Aramendi, J., García Vargas, E., Estaca-Gómez, V., Sánchez, P., Fraile, C., Duque, J., de Francisco Rodríguez, S., González-Aguilera, D., Uribelarrea, D., Mabulla, A., Baquedano, E. & Domínguez-Rodrigo, M.: FLK West (Lower Bed II, Olduvai Gorge, Tanzania): a new early Acheulean site with evidence for human exploitation of fauna. *Boreas*. 10.1111/bor.12243. ISSN 0300-9483.

This paper presents a detailed taphonomic study of the faunal assemblage from FLK West (Olduvai Gorge, Tanzania), a site with an Acheulean component that dates to 1.7 Ma. The faunal sample analysed here is distributed in different archaeological levels and is associated with a significant lithic accumulation including several large format tools and handaxes. The fauna indicates the proliferation of open environments similar to those found in other Bed II and late Bed I sites. Evidence of anthropogenic activity (e.g. defleshing activities and marrow consumption) has been identified in the form of cut and percussion marks. A photogrammetric and morphometric analysis suggests that these marks were produced with quartzite flakes and not with handaxes. Evidence of interaction with carnivores was also noted; tooth marks were observed on some bones. Such interaction indicates the existence of competition between humans and carnivores for the same ecological niche, and might lead us to reflect on the survival strategies of Lower Pleistocene hominins.

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The Acheulean technocomplex is characterized by the production of handaxes, cleavers, picks, large flake blanks, cobbles and tabular clasts (Ambrose 2001; Lycett & Gowlett 2008). The emergence of the Acheulean signals a significant technological change that is currently dated to around 1.7 Ma ago for Kokiselei in Kenya, Konso in Ethiopia and FLK West in Tanzania (Lepre *et al.* 2011; Beyene *et al.* 2013; Diez-Martín *et al.* 2015). Between 1.6–1.4 Ma the Acheulean spread throughout the African continent (Roche *et al.* 2003) and eventually into Eurasia by the end of the Lower Pleistocene (Goren Inbar *et al.* 2002).

The earliest Acheulean is contemporaneous with so-called 'Developed Oldowan' sites at Olduvai, Koobi fora and Peninj (Leakey 1971; Domínguez-Rodrigo *et al.* 2002). The spatio-temporal overlap of these technocomplexes raises several interesting questions, perhaps the most persistent of which concerns functionality. Several authors suggest that Acheulean sites older than 1 Ma may be associated with the processing of wood or plant resources (Keeley 1980; Schick & Toth 1993; Domínguez-Rodrigo *et al.* 2001). This would explain why some Acheulean sites with large accumulations of handaxes (e.g. Olorgesaillie or Peninj) lack butchered faunal remains (Isaac & Isaac 1977; Domínguez -Rodrigo *et al.* 2002) and why other sites, such as TK Lower Floor (Olduvai Gorge), show no direct relation between the fauna and the stone tools found in the same levels (Leakey 1971; Yravedra *et al.* 2016). The poor preservation of bone surfaces at TK did not allow the identification of the agent involved in the bone accumulation. Nevertheless, several green fractures and a single percussion mark have been identified (Yravedra *et al.* 2016). At contemporaneous 'Developed Oldowan' sites (e.g. BK at Olduvai, the ST Complex at Peninj, some sites at Koobi Fora in Kenya, Swartkrans in South Africa), in contrast, the faunal and lithic remains appear to be functionally associated, as bones bear anthropogenic marks (Bunn 1981; Domínguez-Rodrigo *et al.* 2002; Pickering *et al.* 2004; Domínguez-Rodrigo *et al.* 2007,

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2009a, 2014a; Egeland & Domínguez-Rodrigo 2008; Pobiner *et al.* 2009; Organista *et al.* 2015).

The site of Frida Leakey Korongo West (FLKW) at Olduvai has recently provided evidence for the association of early Acheulean tools with carcass exploitation (Diez-Martín *et al.* 2015). In this paper we present a comprehensive taphonomic study of the FLKW fauna from each of the archaeological levels. We also analyse the identified cut marks using a photogrammetric and geometric morphometric approach to determine the type of tool used in the processing of carcasses. Finally, we characterize the palaeoecology of the FLKW fauna in relation to the other Bed II sites.

The site of FLKW

FLKW was discovered in 2013 by The Olduvai Palaeoecology and Paleoanthropology Project (TOPPP). FLKW is located just west of the famous FLK site (Fig. 1) at the base of Bed II (Fig. 2). The chronology of FLKW is situated between 1.698±0.015 and 1.664±0.019 Ma (Fig. 2). These chronological constraints situate FLKW right above Tuff IIA, which was previously dated to *c.* 1.7 Ma. Hay (1976) highlighted that throughout this region, most of Bed II is eroded away by later incision. At locality 45 (FLK) this erosion affected the Lemuta Member and Tuff IIA, creating the first regional discordance identified. The discordance represents a sedimentary change: above the discordance only medium- to high-energy sediments were deposited, in contrast with the underlying waxy clays. FLKW is precisely situated at the base of this transition, before the waxy clays give way to the detritic and erosive sedimentation of the overlying stratigraphical sequence (Diez-Martín *et al.* 2015).

FLKW is located in a fluvial palaeochannel where six stratigraphical levels with fauna and lithic remains have been defined (Diez-Martín *et al.* 2015). Level 6 is a 20-cm-thick matrix-supported conglomerate composed of blocks, cobbles and gravels (2–150 mm) within a matrix of coarse sand. Level 5 is composed of coarse sand. Level 4 is composed of medium-grained sand and well-sorted fine tuffaceous sands. Level 3 is a massive clayish silt without flow structures. Level 2 is an erosive and complex unit, and Level 1 is formed by massive fine-grained homogeneous sand and silt.

A total of 2120 lithic artefacts has been discovered at FLKW. These tools were produced with local raw materials: quartzite, volcanic rocks and chert (Diez-Martín *et al.* 2015). Handaxes and large flakes dominate the assemblage, especially in Levels 5 and 6 (Diez-Martín *et al.* 2015). A preliminary taphonomic study provides direct evidence for the functional association of the lithic artefacts and the faunal remains (Diez-Martín *et al.* 2015), making FLKW one of the few Lower Pleistocene sites with Acheulean tools that can be clearly linked to the consumption of carcasses. Here, we built on that preliminary foundation with a detailed taphonomic and palaeoecological analysis of FLKW.

Fig. 1. Location of FLKW in northern Tanzania (map modified from Hay 1976).

Sample

A total of 1042 remains from FLKW Levels 1–6 was analysed for this study. To analyse the cut marks and determine the kind of stone tool used we compared the morphology and section of the cut marks with experimental marks. The experimental reference sample includes 107 cut marks produced with quartzite flakes from the Naibor Soit, 85 cut marks made with basalt flakes collected at Olduvai Gorge (Maté-González *et al.* 2016) and 122 cut marks produced with handaxes of Naibor Soit quartzite. Quartzite and basalt are the two main raw materials found in the Bed II sites (Hay 1976; Kyara 1999). Basalt outcrops can 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 Olduvai probably derives from Naibor Soit (Hay 1976).

Palaeoecological comparisons were made with assemblages recovered from other sites in Bed II such as HWK3-5, MNK and FCW (Leakey 1971), TK (Yravedra *et al.* 2016), SHK (Domínguez-Rodrigo *et al.* 2014b) and BK (for BK1, BK2 and BK3, see Domínguez-Rodrigo *et al.* (2009b), for BK4 see Domínguez-Rodrigo *et al.* (2014a) and for BK4b see Organista *et al.* (2015)).

Material and methods

Faunal analysis

Taxonomic identifications were based mainly on teeth and reference material. However, in those cases when such determination was not possible, fragments were attributed to animal weight/size classes following Bunn (1982), where 'small-sized' is considered sizes 1 and 2, 'medium-sized' refers to size 3, and 'large' refers to sizes 4–6.

Faunal remains were quantified by number of identifiable specimens (NISP), minimum number of individuals (MNI) and minimum number of elements (MNE).

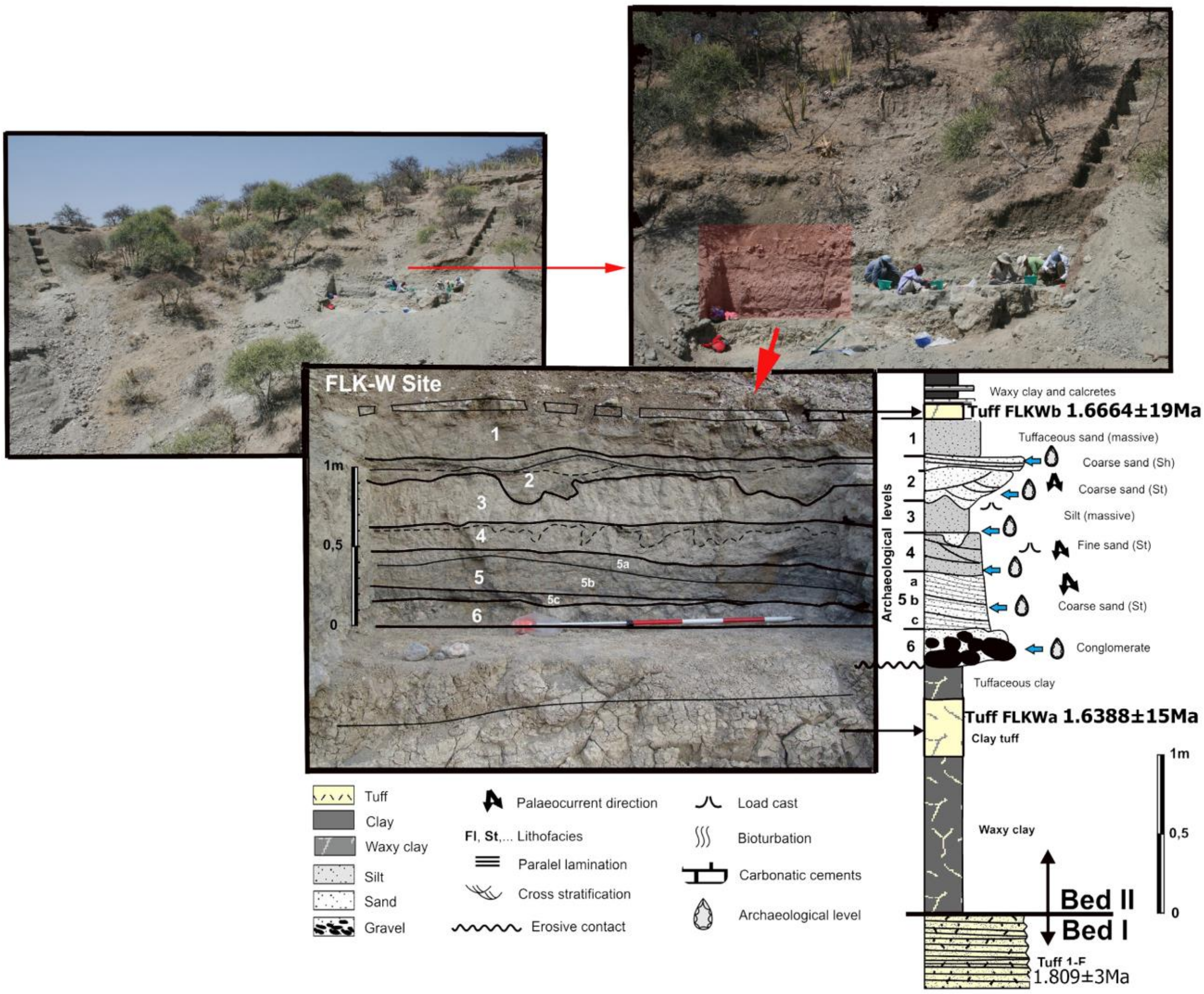

Fig. 2. Stratigraphy of FLKW. Photographs and drawing modified from Diez-Martín *et al.* (2015).

MNE estimates include limb shafts, age, size and biometrics. Elements were quantified according to Yravedra & Domínguez-Rodrigo (2009). For limb bone identifications, factors such as shaft thickness, section shape and medullar surface properties were considered (Barba & Domínguez-Rodrigo 2005). MNI estimates considered element side and ontogenetic age (Brain 1969).

To assess mortality patterns, specimens were assigned to one of three categories based on tooth eruption and crown wear: infantile, juvenile–prime adult and adult.

Skeletal part profiles were organized into four anatomical regions: cranial (i.e. horn, cranium, mandible and teeth), axial (vertebrae, ribs, pelvis and scapula, *sensu* Yravedra & Domínguez-Rodrigo 2009), upper appendicular elements (humerus, radius, ulna, femur, patella and tibia) and lower appendicular elements (metapodial, carpals, tarsals, phalanges and sesamoids). Long limb bones were further divided into upper (humerus and femur), intermediate (radius and tibia) and lower (metapodial) bones (Domínguez-Rodrigo 1997).

Several procedures were followed to reconstruct site formation processes, assess site integrity and evaluate the contribution of various biogenic agents to the faunal assemblage. Bone fragmentation was analysed according to two variables. First, bones were divided into several categories according to their length: <3, 3.1–5.0, 5.1–10 and >10 cm. Second, shaft preservation was classified following Bunn's (1982) circumference types, where type 1 refers to specimens with <50% of the shaft circumference intact, type 2 to specimens with >50% of the shaft circumference intact and type 3 to specimens with an intact shaft circumference.

The impact of water activity was estimated with fragment size distributions and the presence of abrasion, polishing, rounded bones, and carbonates. Signs of polishing, rounding or abrasion would be expected in transported assemblages, but also in non-transported assemblages exposed to circulating water and mobile sediments, such as those encased in sand strata (Thompson *et al.* 2011). Determining whether or not the assemblage is in primary vs. secondary position is particularly important given the fluvial depositional context of the site.

Weathering was analysed following Behrensmeyer (1978). A high degree of weathering can affect the fragmentation and deterioration of bones. It is important to differentiate whether weathering alterations are affecting bones showing green and/or dry (including diagenetic) breakage patterns. To identify both types of breakage we followed Villa & Mahieu's (1991) criteria. Dry breaks result in abundant breaks that are longitudinal and/or transverse to the axis of the bone and breakage planes that are uneven, rough and possess micro-step fractures. Dry breaks are also characterized by cortical medullary surface angles that are close to 90°. In contrast, green-broken specimens frequently have smoother surfaces and more abundant oblique breakage planes.

Additionally, a systematic search for bone surface modifications was carried out with 10–20× hand lenses (Blumenschine 1995). Diagnostic criteria defined by Domínguez-Rodrigo *et al.* (2009b) guided the identification of cut marks, whereas tooth and percussion marks were recorded following Blumenschine (1988, 1995). For comparative purposes, surface modifications include the evaluation of epiphysis and shaft areas (Blumenschine 1988, 1995). Modifications are also quantified by element type and bone section (Domínguez-Rodrigo 1997; Barba & Domínguez-Rodrigo 2005) based on NISP values. The presence of tooth, percussion and cut marks is recorded for the entirety of the remains, although estimated percentages include only well-preserved bone surfaces.

Human and carnivore activity can also be identified through breakage patterns. Notches, for instance, which are semi-circular outlines along the otherwise rectilinear edge of a fracture surface associated with a negative flake scar on the medullary surface (Capaldo & Blumenschine 1994; Domínguez-Rodrigo *et al.* 2007), can be produced by both humans and carnivores. Notches can be classified in four groups: A (single notch), B (incomplete notch), C (double-overlapping notch) and D (double-opposing), with humans and carnivores producing different frequencies of each type. Although the dimensions of notches can be measured, these data typically do not reliably distinguish between the two actors, so they are not reported here. By contrast, the angle of fracture resulting from the action of these agents (dynamic loading in the case of humans and static loading in the case of carnivores) has been demonstrated to be more reliable. The platform angles of bone flakes removed during percussion tend to be more acute/obtuse than those of flakes removed during carnivore bone breakage. Using a goniometer, the platform angle was measured at the loading point on the negative scar of the detached flake.

Geometric morphometric and micro-photogrammetric analysis of cut marks

Cut marks were analysed according to micro-photogrammetric and geometric morphometric analyses. The cut marks were selected on the basis of their preservation and general condition. We excluded those marks that display poor cortical preservation owing to weathering, biochemical alteration or the overlap of tooth marks.

High-resolution images obtained through micro-photogrammetry and computer vision techniques were

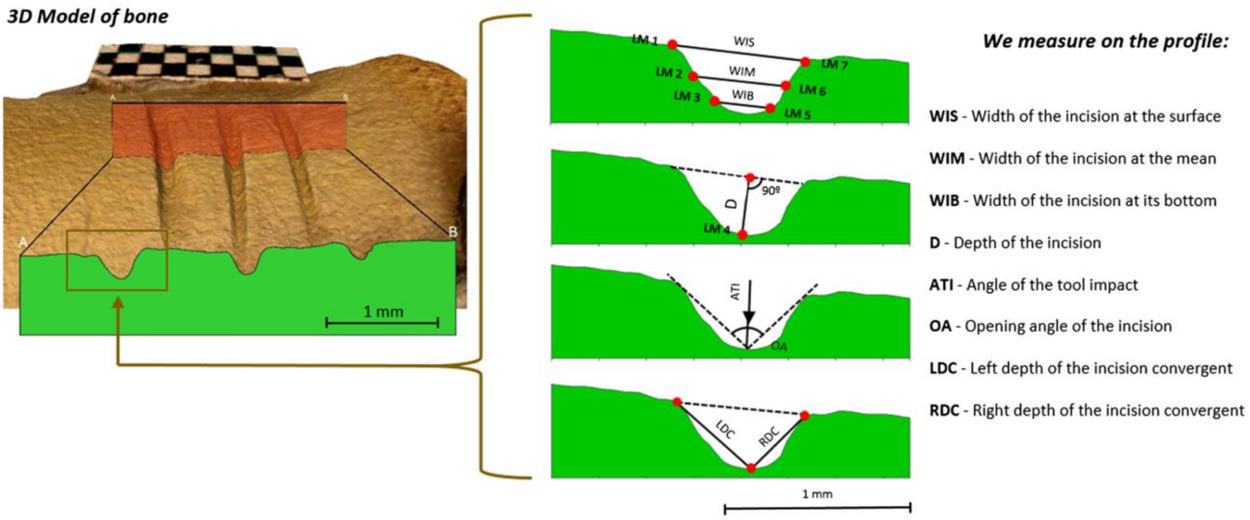

Fig. 3. Cut mark measurements and landmarks used in the geometric morphometric analysis.

used for the 3D modelling of cut mark sections. Following the methodology of Maté-González *et al.* (2015), oblique photographs and micro-photogrammetrics were used to generate precise metrical models of cut marks. A Canon EOS 700D reflex camera with a 60 mm macro-lenses was used. Specimens were individually placed on a photographic table with lighting adjusted in such a way as to keep the bone continuously 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 exposure time 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 provide a precise measurement reference (see Maté-González *et al.* 2015).

Once the photographs had been taken, they were processed to generate a 3D model for each mark. Photographs were treated with photogrammetric reconstruction software packages in *GRAPHOS* (inteGRAted PHOtogrammetric Suite), Agisoft PhotoScan, PIX4D, and PW (González-Aguilera *et al.* 2013, 2016a, b; Maté-González *et al.* 2015). After producing scaled 3D models, *Global Mapper* software was used to define and measure mark profiles as explained in Maté-González *et al.* (2015, 2016). For data collection between nine and 13 photographs were taken for each mark. The number of photographs varied 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 photos acquired.

Our goal with the reconstructions is 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 owing to the similarity of adjacent images. By contrast, if the separation amongst images (baseline) decreases, a better completeness of the object will be

Table 1. Taxonomic profiles at FLKW by NISP and MNI.

Species	Level 1		Level 2		Level 3		Level 4		Level 5		Level 6	
	NISP	MNI	NISP	MNI	NISP	MNI	NISP	MNI	NISP	MNI	NISP	MNI
Bird	1	1										
Tortuca									1	1		
Crocodile	1	1										
Connochaetes sp.									4	2		
Megalotragus sp.			2	1			1	1	1	1	3	1
Alcelaphini 3a	2	2			1	1	1	1	5	2	6	1
Alcelaphini 3b									1	1		
Alcelaphini 2	1	1					5	2	3	1		
Hippotragus gigas									1	1		
Tragelaphini sp.									1	1		
Kobus sp.							1	1				
Antidorcas							1	1				
Gazella sp. size 1							4	1				
Gazella sp. size 2	1	1					4	1	1	1		
Syncerus sp.	1	1									1	1
Pelorovis oldowayensis									1	1		
Giraffidae									1	1	1	1
Kolpochoerus sp. size 2									3	1	1	1
Kolpochoerus sp. size 3	1	1					1	1	2	1	3	1
Metridiochoerus sp.									2	1	6	2
Suidae size 3			1				2	1	1	1	1	1
Elephas sp.	2	1	2	1	2	1	1	1				
Equus oldowayensis	2	1							9	2	8	1
Hipparion cornelianum	1	1									9	3
Rhinocerontidae									1	1		
Hippopotamus sp.	7	2	1	1			10	1				
Crocuta crocuta									1	1		
Indet. size 1							5		4		5	
Indet. size 2	2				3		20		45		24	
Indet. size 3	8		4		6		22		53		35	
Indet. size 3a	3				6		11		39		30	
Indet. size 3b	2				1		7		22		46	
Indet. size 4	12		2		1		17		40		36	
Indet. size 5	12		1		2		11		7		12	
Indet. size 6					1		2		3		2	
Indet.	17		18		14		84		105		103	
Total	76		31		37		210		357		332	

Table 2. Skeletal profiles (MNE) of Levels 1, 2, 3, 4, 5 and 6. where small includes sizes 1 and 2; middle, sizes 3, 3a, 3b; and large, sizes 4, 5, 6.

	Level 1 MNE			Level 2 MNE			Level 3 MNE			Level 4 MNE			Level 5 MNE			Level 6 MNE		
	Small	Middle	Large	Small	Middle	Large	Small	Middle	Large	Small	Middle	Large	Small	Middle	Large	Small	Middle	Large
Horn								1		2				1	1		2	
Skull			1					1					2	4	2	1	2	1
Maxilla													1	1		1	1	
Mandible			2			1				2		2		2	1	1	2	1
Teeth	3	4	13		5	4		2	1	10	8	5	4	25	4	0	29	3
Vertebrae		1	2				1		2	3	2	8	4	5	6	2	3	3
Rib		1	4			1		1		2	2	2	1	4	4	1	6	2
Scapula											1	0	2	3	1		2	
Humerus																		
Proximal end												1		1		1		
Shaft	1	1	1					1			2		3	3	1	1	2	3
Distal end		1									1		1	1	1	1		
Radius																		
Proximal end			1								1			1			2	
Shaft	1	1	1					1			1		1	3			1	1
Distal end			1									1	2	1		1		1
Ulna								1			1		1	1	1		1	
Carpal					1						2	2	1	2	1			1
Metacarpal																		
Proximal end													1	1			3	
Shaft					1						1		2	2				
Distal end											2		1	1				
Pelvis			1							1	1				2		3	1
Femur																		
Proximal end															1		1	1
Shaft								1			1		1	4		1	1	2
Distal end		1									1	1			1		2	1
Tibia																		
Proximal end											1						1	
Shaft	1	1				1	1	2		2	3		3	5	1	2	6	3
Distal end										1	1		2				1	
Patella																		
Tarsal										1			2	2		1		
Metatarsal																		
Proximal end												1		1	1	1	1	
Shaft								1		2	2		2	2	1	2	3	1
Distal end										1	1		2		1		1	
Metapodial																		
Proximal end		1											1					
Shaft													2				3	
Distal end													1					
Phalange											1	1		2		1	1	
Sesamoid					1					2				1	1			
Total	6	11	25	0	8	6	2	12	3	29	36	24	43	79	32	18	80	25

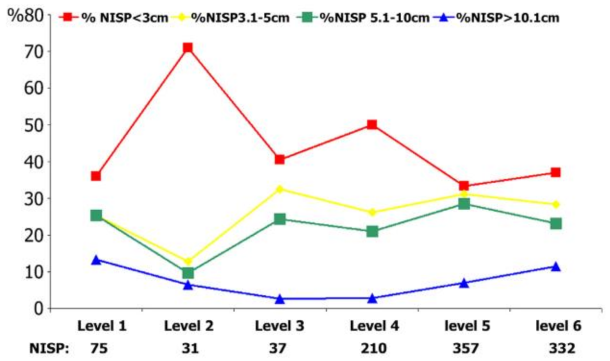

Fig. 4. Frequency of occurrence of specimens according to maximum length.

obtained, but the accuracy will be poorer because of a worse intersection of the perspective rays.

To contextualize the accuracy analysis of photogrammetric and geo-informatic (PG) methods vs. microscopy given that geometric data are dependent from two different sources (scaling and photogrammetric reconstruction-PHO), the precision of the PG was 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 (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 geometric and statistical levels.

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. A series of measurements including WIS, WIM, WIB, OA, D, LDC, RDC (*sensu* Bello *et al.* 2013) were taken on the mark section and used as quantitative variables (Fig. 3).

The measurements for each mark section were later compared with experimental samples of cut marks produced with flakes and handaxes (Fig. S1) made from quartzite and basalt obtained within the Olduvai Basin (Maté-González *et al.* 2016). In this case, seven identical landmarks per section – as shown in Fig. 6 (LM 1–7) – were considered for each mark. 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 correspond to the measures considered for the statistical analysis (Fig. 3). 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 at approximately 10% of the right end of the mark (Fig. 3); LM4 was at the very end; LM5, LM6 and LM7 were placed opposite LM3, LM2 and LM1, respectively. The resulting tps file was imported into R (R freeware, www.r-project.org) and analysed using the 'geomorph' library (Sherratt 2014). We conducted a geometric morphometric bidimensional analysis of the seven landmarks (see Fig. LM1–7 of Fig. 6), which were first subjected to a generalized Procrustes analysis (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. We have incorporates a multivariate principal components analysis (PCA). The PCA estimates similarities and differences of marks on a bidimensional Euclidean space. Plotting of the PCA with confidence ellipses was carried out with the ggplot2 R library. Lastly, a discriminant linear analysis (DLA) was performed to estimate the differences amongst the several groups of marks defined by raw materials. The DLA function is included in the MASS R package.

Palaeoecological analyses

For the palaeoecological analysis we compared the taxonomic profiles of FLKW with those identified at other Bed II sites. Animal species were grouped according to their palaeoecological characteristics, and were plotted in three separate groups: (i) those corresponding to wooded ecosystems, (ii) those corresponding to water sources and (iii) those corresponding to open savanna biomes.

Animal species were distinguished and tabulated (using MNI) by tribe. This analysis allows the discrimination of species and of the types of environments that are represented. A ternary plot was used to group the data from FLKW and other Bed II sites and then link these data to the major bovid tribes of Africa. The ternary graph was programmed in R (library ggtern) using all the data from

Table 3. Modifications produced by carnivores.

Level	1	2	3	4	5	6
NISP with good surface preservation	15	5	22	69	142	129
NISP with tooth marks	5		1	7	11	8
% NISP with tooth marks	33.3		4.5	10.1	7.8	6.2
NISP with furrowing	2 (1 fem., 1 hum.)				1 hum.	1 hum.
% NISP with furrowing respect to long bones	33% hum. and 100% fem.				5.5% hum.	5.5% hum.

each bovid group. The bovid groups considered were Alcelaphini and Antilopini, Reduncini and Bovini, and Tragelaphini and Aepycerotini.

Results

Taxonomical, mortality and skeletal profiles

The FLKW fauna includes a large array of species (Table 1), although it is dominated by open-habitat taxa. Alcelaphines, antilopines and equids are the most common taxa throughout the stratigraphical sequence. Other animals associated with the presence of water such as *Hippopotamus*, or species adapted to mixed environments such as *Kobus* and *Tragelaphus*, do also appear in some levels.

Levels 1, 2 and 3 are the least representative of the sequence. Only 75 remains were found in Level 1, 31 in Level 2 and 37 in Level 3, representing at a minimum 12, three and two individuals, respectively (Table 1). These MNIs are probably underestimates because indeterminate remains assigned to size 2–6 animals were not considered. Alcelaphini is the most commonly represented tribe, appearing in all three levels. Elephant remains were also observed in all levels, but are not as abundant. Suidae and buffalo are only represented in Level 1, as well as gazelles and equids (both *Equus* and *Hipparion*). Finally, *Hippopotamus* appears in Levels 1 and 2. Level 1 shows the widest taxonomic range, with a total of eight mammal species represented in addition to two bird and two reptile species. In Level 1 species adapted to open areas co-occur with species associated with watercourses (e.g. hippopotamus, crocodile and buffalo).

Levels 4–6 preserve much higher frequencies of remains, with more than 200 specimens representing more than 10 individuals in each level. Level 4 has a wide faunal range with eight species, most of them adapted to open areas. This level also includes species such as waterbuck and hippopotamus that require the presence of water in the vicinity. Level 5 also shows wide faunal diversity, with a total of 12 identified species. Amongst the Level 5 species, there is a clear predominance of animals adapted to open environments (Alcelaphini, Antilopini, Suidae, *Rhinoceros,* Giraffidae). Species best suited to bushy habitats such as Tragelaphini and *Pelorovis* are also present. Level 6 has a less diverse fauna and open-habitat species are clearly predominant.

Age patterns suggest a predominance of adult individuals. No infants were identified and only two juveniles were found in Level 1 – one *Hippopotamus* and one Alcelaphini size 3a.

As mentioned above, the upper levels are not very representative as they contain few elements (Table 2). Only in Level 1, there are more than 20 elements belonging to large animals; most of these are cranial elements, although axial and appendicular bones are also present.

Table 4. Frequency of notch types at FLKW according to the types defined by Capaldo & Blumenschine (1994) and Domínguez-Rodrigo *et al.* (2007).

Level	1	2	3	4	5	6
Notches	1		1	2	7	7
Notches Type Single (a)			1 (100)	1 (50)	3 (43)	3 (43)
Notches Type Incomplete (b)					2 (29)	1 (14.3)
Notche Type Double (c)	1 (100)			1 (50)	1 (14)	3 (43)
Notches Type Opposing (d)					1 (14)	

Levels 2 and 3 have very few elements and those are mainly cranial elements. In Level 3 only middle-sized animals are present, accounting for >10 elements, including teeth and long bone shafts (Table 2). Owing to the small sample sizes no significant conclusions could be drawn, although the absence of epiphyses and the low axial MNE are notable.

Levels 4–6 show a more even skeletal representation; almost all taxonomic groups are represented by more than 20 elements. Nevertheless, in proportion to the MNI, a large osteological bias is apparent. In Level 4, for example, there are bones of all taxonomic groups, but within each group there are certain anatomical elements missing. Amongst small-sized animals cranial elements are abundant, especially teeth, whereas appendicular and axial elements are scarce. Medium-sized animals are better represented by appendicular elements than by axial and cranial bones. Amongst large-sized species there are more axial elements than appendicular elements (Table 2).

Level 5 shows a similar pattern. In this level, small-sized animals are well represented by axial and appendicular elements, but cranial bones appear less frequently. Medium-sized species are represented by bones of all sections, but proportionally there is a lack of axial elements and long bone epiphyses. Large-sized animals

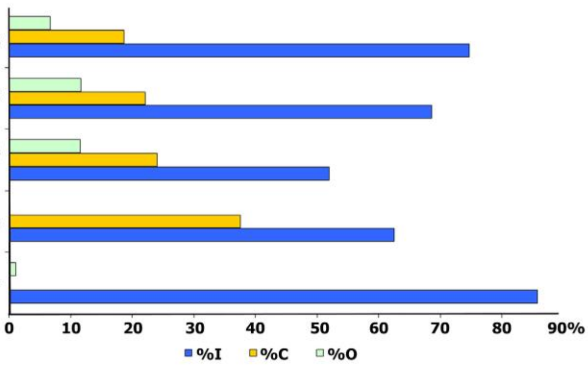

Fig. 5. Circumference types for long bones according to Bunn (1982), where I: <50%, C: >50% and O: complete circumference.

Table 5. Main human modifications at FLKW.

Level	1	2	3	4	5	6
NISP with good surface preservation	15	5	22	69	142	129
NISP with cut marks				1	4	1
% NISP with cut marks				1.5	2.8	0.8
NISP with percussion marks			3	1	8	9
% NISP with percussion marks			13.6	1.5	5.6	7

are as well represented as in Level 4, with a significant scarcity of appendicular elements.

Few elements – mainly appendicular elements – belong to small-sized animals in Level 6. Medium-sized species are mostly represented by appendicular and cranial elements, whereas the axial skeleton appears underrepresented. Finally, large animals show the opposite trend to that seen in Levels 4 and 5, as appendicular elements predominate over axial bones (Table 2).

Each level and each taxonomic group shows a different pattern of representation. Only two global patterns can be detected. First, there is a scarcity of elements in relation to the MNI estimates; this suggests a large preservation bias. Secondly, such bias seems to mainly affect axial elements amongst small- and medium-sized animals. By contrast, the axial skeleton of large species is proportionately better represented than other skeletal sections (Levels 1, 3, 4 and 5). Regarding the proportion of epiphyses vs. shafts, several results can be highlighted (Table 2). In the lower levels, shafts are more abundant than epiphyses, although the differences are not significant; only medium-sized animals in Level 5 show a considerable bias in this regard (Table 2).

The taphonomic study

Taphonomic analyses may help explain the representation bias observed in the assemblage. These indicate that fragmentation was not very intense. In most levels, bones <3 cm make up only 33–50% of the total assemblage. The levels showing a greater fragmentation are Level 4 with 50% of bones <3 cm and Level 2 with 71% of specimens <3 cm (Fig. 4).

Regarding bone surface modifications, the impact of water is evident. The location of the site in a fluvial palaeochannel resulted in 44.3% (Level 4) and 67.7% (Level 2) of the remains showing hydraulic alterations such as abrasion, polishing and rounding (Table S1). These modifications were identified on the edges of green fractures, which suggests that water acted on previously fractured samples. Water action also resulted in the precipitation of carbonates on the surface of the bones and the appearance of calcareous concretions on a large proportion of the assemblage (Table S1).

The action of water flows could have caused the movement of bones that are more prone to be transported off site. According to Voorhies (1969) and Behrensmeyer (1975, 1982) small and less dense elements are more easily transported by water. This means that epiphyses and axial elements are more likely to disappear than other bones (e.g. mandible).

The representation bias described in Tables 1 and 2 could have been produced by the action of water, as ‘transportable’ (Voorhies group I) elements such as ribs and vertebrae are scarce. However, this does not explain why other, less easily transported elements such as mandibles are also scarce. This interpretation of water action conflicts with the fact that more than 40% of specimens are <3 cm (Fig. 4). Thus, although water action appears to have affected bone surfaces, it does not explain all of the observed osteological bias.

Other bone surface modifications such as weathering or biochemical alterations are rare (Table S1) and there is a predominance of bones with green fractures (Table S2).

The representation bias may also be explained by the action of carnivores. Some tooth marks were identified on the fossil assemblage, including pits, scores, punctures and furrowing (Tables S3). Notch types C and D, which are usually related to the action of carnivores, were observed in Levels 1 and 3–6 (Table 4).

Tooth mark frequencies are low except in Level 1. Furrowing is not intense (Table 3), and there are usually no more than five tooth marks per bone, even when pits and scores were observed on the same specimen. In addition, epiphyseal representation is not extremely low (Table 2). In Levels 3–6 long bone breakage patterns correspond to type 1 (<50% of the circumference is left) instead of being complete (Fig. 5).

Anthropogenic activity was documented in the lower levels of the sequence. Cut marks were identified in Levels 4–6, suggesting defleshing and disarticulation activities (Tables 5, 6). The presence of percussion marks (table 5 and figs S25–S28 of Diez-Martín *et al.* 2015) and the predominance of notch types A and B in Levels 3–6 (Table 4) suggest that in addition to defleshing activities, hominins also extracted the marrow from some long bones. There are several percussion marks on the long bone shafts (tibiae, radii, humeri) of medium-sized individuals (4–5). The recovery of three impact flakes

Table 6. Anatomical distribution of cut marks at FLKW.

Anatomical distribution	Animal size	Level 4	Level 5	Level 6
Femur shaft	3	Defleshing		
Metatarsal shaft	4		Defleshing	
Rib	3		Disarticulation	
Tibia shaft	4		Defleshing	
Humerus shaft	3a		Defleshing	
Tibia shaft	3b			Defleshing or disarticulation

Fig. 6. Cut mark on a metatarsal and its cross-section. The cross-section was obtained with the aid of photogrammetric means.

belonging to size 3/3b animals in Levels 5 and 6 also points to an anthropogenic contribution to the assemblage.

The notch angles are either very acute (66°) or very obtuse (120°), which matches the pattern produced by human activity. It is still unknown whether humans were primarily responsible for the accumulation of carcasses at FLKW. However, it seems clear that hominins had access to meat resources, as evidenced by the cut marks on diaphyseal sections of upper limb bones (e.g. humerus and femur; Table 6). It has also been demonstrated that hominins practiced an intensive exploitation of the resources to obtain the marrow.

Geometric morphometric and micro-photogrammetric analysis of cut marks

As we detected a clear association between the fauna and lithic industry at FLKW, we decided to conduct an analysis to determine the kind of tools used at FLKW for the exploitation of the carcasses. The presence of handaxes in the same space as bones with cut marks could suggest that handaxes were used to process the carcasses. Here we present the results obtained after a detailed analysis of FLKW cut marks that involves the creation of 3D models. Such models are based on the use of oblique photography with a reflex camera with a

Fig. 7. Cut marks on a femur and their cross-sections. The cross-sections were obtained with the aid of photogrammetric means.

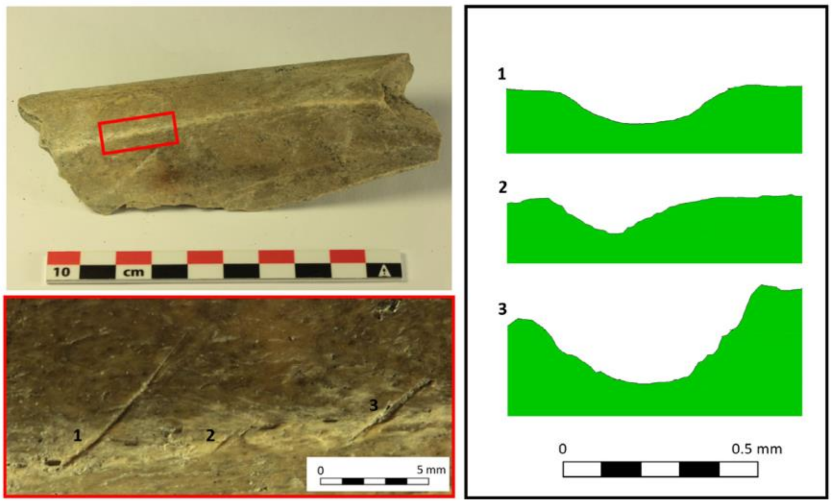

Fig. 8. Cut marks on a tibia and their cross-sections. The cross-sections were obtained with the aid of photogrammetric means.

macro-lens (average GSD (mm) = ±0.0078; average scaling error (mm) = ±0.0157; average photogrammetric error (mm) = ±0.0058; average precision (mm) = ±0.0168).

Our high-quality 3D reconstructions show cut marks with a U-shaped section (Figs 6–8). This shape has been traditionally used to define scores generated by teeth, instead of cut marks that are usually described as V-shaped marks (Binford 1981). Thus these results could generate some confusion. However, it must be taken into account that the FLKW marks were affected by the action of water. All the bones with cut marks show a certain degree of polishing and abrasion, which has generated cut marks with U-shaped (Figs 6, 8) or open V-shaped (Figs 7, 8) cross-sections.

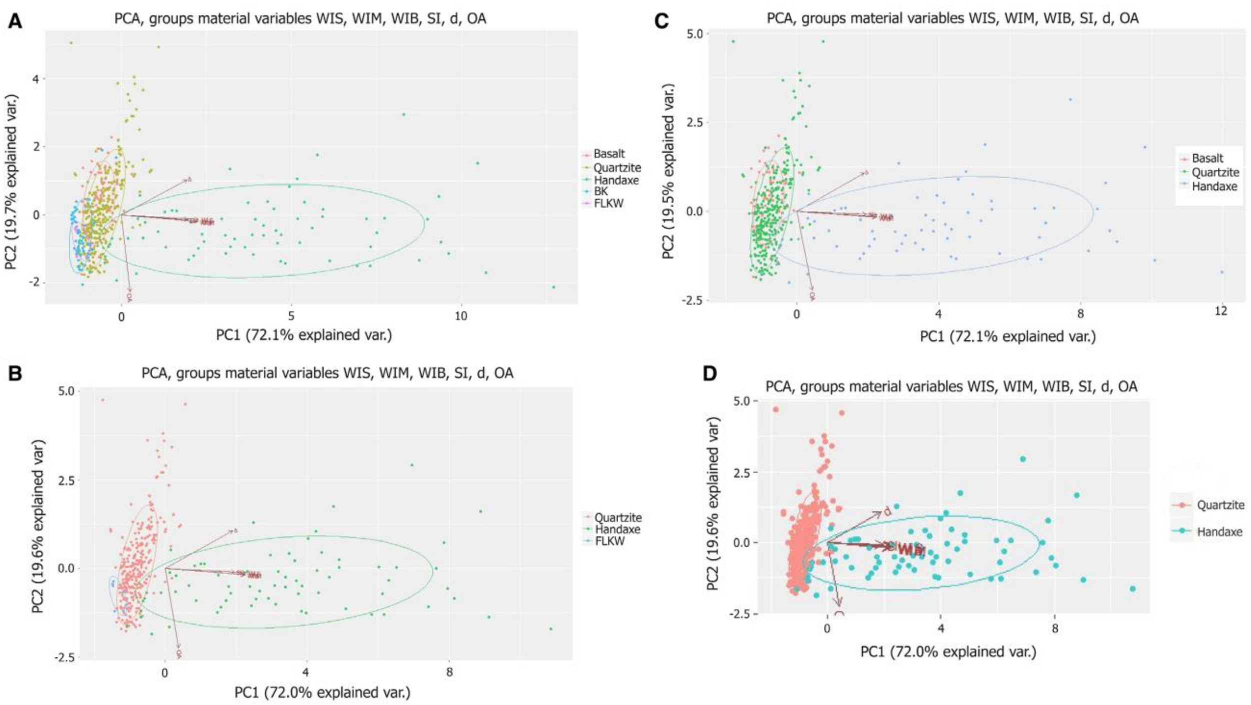

Fig. 9. PCA plot comparing cut marks produced with: A. Simple quartzite and basalt flakes with those generated with the experimental quartzite handaxe, and the cut marks identified at BK and FLKW. B. Simple quartzite flakes with those generated with the experimental quartzite handaxe, and the cut marks identified at FLKW. C. Simple quartzite and basalt flakes with those generated with the experimental quartzite handaxe. D. Simple quartzite flakes with those generated with the experimental quartzite handaxe. See Material and methods section for detailed description of WIS, WIM, WIB, SI, d, OA.

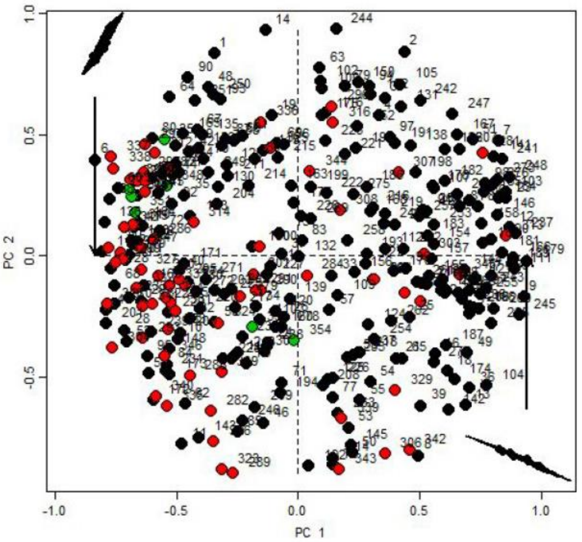

Fig. 10. PCA plot of the morphometric analysis, where cut marks identified at FLKW are plotted in green, cut marks produced with simple quartzite flakes are red and cut marks generated with the experimental quartzite handaxes are black.

Keeping this in mind, we compared the FLKW cut marks with those created in previous experiments with flakes and handaxes made from quartzite and flakes made from basalt.

PCA results including biometric data (Figs 9, 10) show that the FLKW cut marks are different from those generated in our experiments using a quartzite handaxe (Fig. 9A, B). The marks generated with the experimental quartzite handaxe are also different from those created with quartzite and basalt flakes (Fig. 9). Cut marks produced with the experimental handaxe are wider as a result of the double-sided tool edge. The FLKW marks fit with the group that includes the marks produced with quartzite flakes (Fig. 9A, B), being slightly different from those produced with basalt flakes (Fig. 9A). These results suggest that the FLKW marks were generated with simple (probably quartzite) flakes rather than handaxes.

It should be noted that the experimental handaxe marks are not only different from those produced with simple quartzite and basalt flakes but also from the cut marks identified at Bed II sites such as BK (Fig. 9A, C). The PCA results including morphometric data (Fig. 10) show the same results as in Fig. 9. The FLKW marks cluster with cut marks produced with simple flakes.

Following the experimental work with handaxes of Bello *et al.* (2009) in Boxgrove and their conclusions, it should be stressed that morphological differences amongst cut marks can be the result of different levels of hand pressure rather than the use of different types of raw materials or tool. However, as the FLKW cut marks were clustered with the cut marks made with quartzite flakes and the BK cut marks (Fig. 9A, B), we opted for this interpretation, given the lack of proper experimental analogues for documenting how hand pressure impacts the morphological range of cut marks.

Although the cut marks at FLKW were not produced with handaxes, the presence of percussion marks and bones with green fractures on the site could allow the interpretation that bones were broken using handaxes. However, this can only be considered as a possibility. Choppers and hammers are frequent in FLKW and those could also have been used to break the bones. Only future experimental bone-breaking analyses with handaxes will allow us to know if handaxes were used in the breakage of bones at the site.

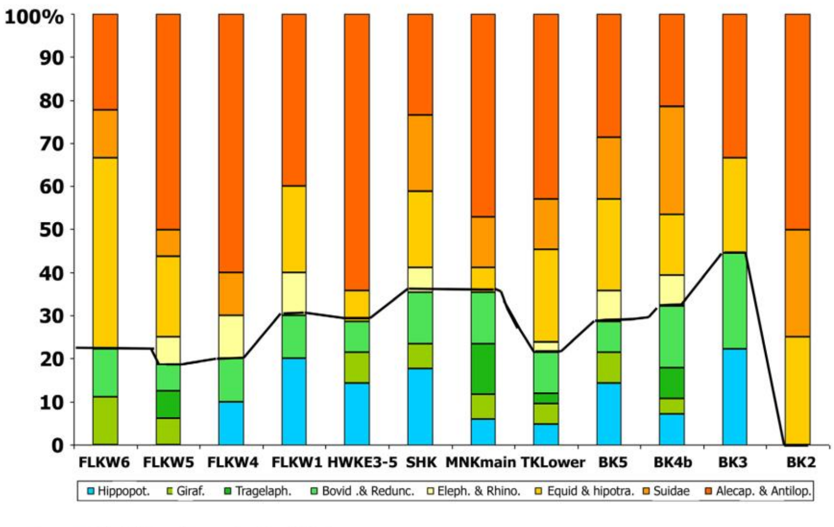

Fig. 11. Faunal representation and MNI at the main Bed II sites.

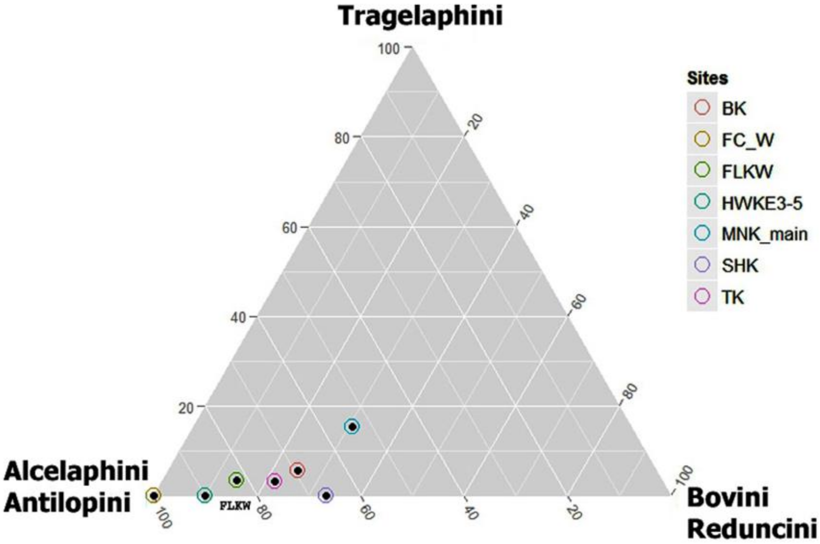

Fig. 12. Ternary graph programmed in R, using all the data from each bovid group (Alcelaphini and Antilopini, Reduncini and Bovini, and Tragelaphini and Aepycerotini) found at different Olduvai sites.

Palaeoecological analyses

Palaeoecological analyses indicate that the landscape surrounding FLKW was open (Figs 11, 12). Animals adapted to open areas such as Alcelaphini, equids, Suidae, Antilopini, Rhinocerontidae and Proboscidea appear in the studied FLKW levels. Species more suited to forested habitats and hippopotamus are scarce and do not exceed 30% of the MNI. These patterns are consistent with the trends observed at other Bed II sites. For example, at HWKE, open-habitat species also make up 70% of the total MNI (Fig. 11).

The bovid record of several Olduvai Bed II sites (e.g. SHK, TK, BK) shows a predominance of species adapted to open environments (Fig. 12), which confirms previous interpretations on the openness of landscapes during Bed II times (Domínguez-Rodrigo *et al.* 2014a, b).

Conclusions

Several conclusions can be drawn from this study. On the one hand, the taphonomic analysis demonstrated that the FLKW fossil assemblage was not created by abiotic external processes (e.g. the action of water), although it was impacted by them. The presence of a large amount of small bone fragments, and a significant number of epiphyseal and axial elements indicate that water flows did not play a major role in the formation of the site. On the other hand, the identification of certain surface modifications associated with the action of water such as polishing, rounding and abrasion indicate the presence of at least low-to-moderate energy water flows that transported abrasive sediments that ultimately altered the bone surfaces and may even have created assemblages.

Skeletal profiles show that many anatomical elements are missing. Even though only a small area of the site has been excavated, we found some evidence that might explain the bias identified at FLKW. The activity of carnivores was documented in the form of tooth marks and notches. Although carnivore impact is not very significant, especially in Levels 4–6, it could have affected the original representation of the fossil record at FLKW.

Regarding human activity, FLKW appears to be one of the first early Acheulean sites showing a clear functional association between some of the fauna and the lithic assemblage. There are some other Acheulean sites (e.g. TK) where carcasses appear in association with stone tools, but no cut marks could be identified to demonstrate their functional association. At FLKW, cut and percussion marks as well as notch type distribution suggest that some large animals (sizes 3–5) were processed by humans.

The impact of humans on the FLKW assemblage, especially in Levels 4–6 is worth discussing. Even though data are scarce, we have enough evidence to hypothesize about the degree of anthropogenic impact on the site. Although cut marks do not appear in abundance, their anatomical location on the midshafts of long bones (e.g. femur and humerus) and on ribs suggest early access to meat. Levels 4–6, which preserve more significant human activity in the form of cut and percussion marks than the other levels, show a lesser degree of carnivore action. In these levels tooth mark frequencies are low and epiphyses are relatively common. Future excavations and the analysis of new recovered material will provide more complete results. Currently available data suggest that humans played a role in the modification of the FLKW fossil collection, but no definite conclusions can be drawn at this point.

The photogrammetric and morphometric analyses of cut marks suggest that the marks were produced with quartzite flakes instead of handaxes. Thus, the FLKW handaxes do not seem to be related to the exploitation of carcasses, which suggests that these tools were used for different purposes.

Finally it should be noted that FLKW demonstrates the existence of open landscapes during lower Bed II times at Olduvai. Open habitats have already been observed in the upper levels of Bed I at sites like FLKN and probably spread during Bed II times.

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References

Ambrose, S. 2001: Paleolithic technology and human evolution. *Science 291*, 1748–1753.

Barba, R. & Domínguez-Rodrigo, M. 2005: The taphonomic relevance of the analysis of bovid long limb bone shaft features and their application to element identification: study of bone thickness and morphology of the medullary cavity. *Journal of Taphonomy 3*, 17–42.

Behrensmeyer, A. K. 1975: The taphonomy and paleoecology of Plio-Pleistocene vertebrate assemblages east of lake Rudolf, Kenya. *Bulletin of the Museum of Comparative Zoology 146*, 473–578.

Behrensmeyer, A. K. 1978: Taphonomic and ecological information from bone weathering. *Paleobiology 4*, 150–162.

Behrensmeyer, A. K. 1982: Time resolution in fluvial vertebrate assemblages. *Paleobiology 8*, 211–227.

Bello, S. M., 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. *Journal of Archaeological Science 40*, 2464–2476.

Bello, S. M., Parfitt, S. A. & Stringer, C. B. 2009: Quantitative micromorphological analyses of cut marks produced by ancient and modern handaxes. *Journal of Archaeological Science 36*, 1869–1880.

Beyene, Y., Katoh, S., WoldeGabriel, G., Hart, W. K., Uto, K., Sudo, M., Kondo, M., Hyodo, M., Renne, P. R., Suwa, G. & Asfaw, B. 2013: The characteristics and chronology of the earliest Acheulean at Konso, Ethiopia. *Proceedings of the National Academy of Sciences of the United States of America 110*, 1584–1591.

Binford, L. R. 1981: *Bones: Ancient Men and Modern Myths.* 320 pp. Academic Press, London.

Blumenschine, R. J. 1988: An experimental model of the timing of hominid and carnivore influence on archaeological bone assemblages. *Journal of Archaeological Science 15*, 483–502.

Blumenschine, R. J. 1995: Percussion marks, tooth marks, and experimental determinations of the timing of hominid and carnivore access to long bones at FLK Zinjanthropus, Olduvai Gorge, Tanzania. *Journal of Human Evolution 29*, 21–51.

Brain, C. K. 1969: The contribution of Namib desert Hottentots to understanding of Australopithecus bone accumulations. *Scientific Papers in Namibian Desert Research Station 32*, 1–11.

Bunn, H. T. 1981: Archaeological evidence for meat-eating by Plio-Pleistocene hominids from Koobi Fora and Olduvai Gorge. *Nature 291*, 574–577.

Bunn, H. T. 1982: *Meat-eating and human evolution, studies on the diet and subsistence patterns of Plio-Pleistocene hominids in East Africa.* Ph.D. thesis, University of California at Berkeley, 384 pp.

Capaldo, S. D. & Blumenschine, R. J. 1994: A quantitative diagnosis of notches made by hammerstone percussion and carnivore gnawing on bovid long bones. *American Antiquity 59*, 724–748.

Diez-Martín, F., Sánchez Yustos, P., Uribelarrea, D., Baquedano, E., Mark, D., Mabulla, A., Fraile, C., Duque, J., Díaz, I., Pérez-González, A., Yravedra, J., Egeland, C. P., Organista, E. & Domínguez-Rodrigo, M. 2015: The origin of The Acheulean: the 1.7 million-year-old site of FLKWest, Olduvai Gorge (Tanzania). *Scientific Reports 5*, 17839, doi: 10.1038/srep17839.

Domínguez-Rodrigo, M. 1997: Meat eating by early hominids at FLK Zinj 22 Site, Olduvay Gorge Tanzania, an experimental approach using cut-mark data. *Journal of Human Evolution 33*, 669–690.

Domínguez-Rodrigo, M., Barba, R. & Egeland, C. P. 2007: *Deconstructing Olduvai.* 307 pp. Springer, New York.

Domínguez-Rodrigo, M., Bunn, H. T., Mabulla, A. Z. P., Baquedano, E., Uribelarrea, D., Pérez-González, A., Gidna, A., Yravedra, J., Diez-Martín, F., Barba, R., Arriaza, M. C., Egeland, C. P., Organista, E. & Ansón, M. 2014b: On meat eating and human evolution, a taphonomic analysis of BK4b, Upper Bed II, Olduvai Gorge, Tanzania and its bearing on hominin megafaunal consumption. *Quaternary International 323*, 129–152.

Domínguez-Rodrigo, M., Bunn, H. T. & Yravedra, J. 2014a: A critical reevaluation of bone surface modification models for inferring fossil hominin and carnivore interactions through a multivariate approach: Application to the FLK Zinj archaeofaunal assemblage (Olduvai Gorge, Tanzania). *Quaternary International 322*, 32–43.

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

Domínguez-Rodrigo, M., de La Torre, I., De Luque, L., Alcalá, L., Mora, R., Serrallonga, J. & Medina, V. 2002: The ST site complex at Peninj, West Lake Natron, Tanzania: implications for early hominid behavioural models. *Journal of Archaeological Science 29*, 639–665.

Domínguez -Rodrigo, M., Mabulla, A., Bunn, H. T., Barba, R., Diez-Martín, F., Egeland, C. P., Espilez, E., Egeland, A., Yravedra, J. & Sánchez, P. 2009a: Unravelling hominin behaviour at another anthropogenic site from Olduvai Gorge Tanzania, new archaeological and taphonomic research at BK, Upper Bed II. *Journal of Human Evolution 57*, 260–283.

Domínguez-Rodrigo, M., Serrallonga, J., Juan-Tresserras, J., Alcala, L. & Luque, L. 2001: Woodworking activities by early humans: a plant residue analysis on Acheulian stone tools from Peninj (Tanzania). *Journal of Human Evolution 40*, 289–299.

Egeland, C. P. & Domínguez-Rodrigo, M. 2008: Taphonomic perspectives on hominid site use and foraging strategies during Bed II times at Olduvai Gorge, Tanzania. *Journal of Human Evolution 55*, 1031–1052.

González-Aguilera, D., Guerrero, D., Hernández-López, D., Rodríguez-González, P., Pierrot, M. & Fernández-Hernández, J. 2013: *PW, Photogrammetry Workbench.* Available at: http://www.isprs.org/catcon/catcon6.aspx (accessed 30.04.2014).

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. Abstract: XXIII ISPRS Conference, 12–19 July 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. Abstract: CAT-

CON7-ISPRS. Conference, 12–19 July 2016, Prague, Czech Republic.

Goren Inbar, N., Werker, E. & Feibel, C. S. 2002: *The Acheulian Site of Gesher Benot Ya'aqov: The Wood Assemblage*. 120 pp. Oxbow Books, Oxford.

Hay, R. 1976: *Geology of the Olduvai Gorge*. 220 pp. University of California Press, Berkeley.

Isaac, G. L. & Isaac, B. 1977: *Olorgesailie: Archaeological Studies of a Middle Pleistocene Lake Basin in Kenya*. 272 pp. University of Chicago Press, Chicago.

Keeley, L. H. 1980: *Experimental Determination of Stone Tool-use: a Microwear Analysis*. 226 pp. University of Chicago Press, Chicago.

Kyara, O. A. 1999: *Lithic raw materials and their implications on assemblage variation and hominid behaviour during Bed II, Olduvai Gorge*, Tanzania. Ph.D. thesis, University of Rutgers, 438 pp.

Leakey, M. D. 1971: *Olduvai Gorge. Vol 3. Excavations in Beds I and II. 1960-1963*. 328 pp. Cambridge University Press, Cambridge.

Lepre, C., Roche, H., Kent, D. V., Harmand, S., Quinn, R. L., Brugal, J. P., Texier, P. J., Lenoble, A. & Feibel, C. S. 2011: An earlier origin for the Acheulean. *Nature 477*, 82–85.

Luhmann, T., Robson, S., Kyle, S. & Boehm, J. 2013: *Close-Range Photogrammetry and 3D Imaging*. 1012 pp. Walter De Gruyter, Berlin.

Lycett, S. J. & Gowlett, A. J. 2008: On questions surrounding the Acheulean tradition. *World Archaeology 40*, 295–315.

Maté-González, M. A., Palomeque-González, J. F., 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*. In press, doi: 10.1007/s12520-016-0401-5.

Maté-González, M. A., Yravedra, J., González-Aguilera, D., Palomeque-González, J. F. & Domínguez-Rodrigo, M. 2015: Micro-photogrammetric characterization of cut marks on bones. *Journal of Archaeological Science 62*, 128–142.

Organista, E., Domínguez-Rodrigo, M., Egeland, C., Uribelarrea, D., Mabulla, A. & Baquedano, E. 2015: Did Homo erectus kill a Pelorovis herd at BK Olduvai Gorge? A taphonomic study of BK5. *Archaeological, Anthropological Sciences 8*, 601, doi: 10.1007/s12520-015-0241-8.

Pickering, T. R., Domínguez-Rodrigo, M., Egeland, C. P. & Brain, C. K. 2004: New data and ideas on the foraging behaviour of Early Stone Age hominids at Swartkrans Cave, South Africa. *South African Journal of Science 100*, 215–218.

Pobiner, B., Rogers, M. J., Monahan, C. M. & Harris, J. W. 2009: New evidence for hominin carcass processing strategies at 1.5 Ma, Koobi Fora, Kenya. *Journal of Human Evolution 55*, 103–130.

Roche, H., Brugal, J. P., Delagnes, A., Feibel, C., Harmand, S., Kibunjia, M., Prat, S. & Texier, P. J. 2003: Les sites archéologiques plio-pléistocènes de la formation de Nachukui, Ouest-Turkana, Kenya: bilan synthétique 1997–2001. *Comptes Rendus Palevol Journal 2*, 663–673.

Schick, K. & Toth, N. 1993: *Making Silent Stones Speak*. 352 pp. Simon and Schuster, New York.

Sherratt, E. 2014: *Quick Guide to Geomorph v. 2.0*. Available at: http://www.public.iastate.edu/~dcadams/PDFPubs/Quick%20Guide%20to%20Geomorph%20v2.0.pdf.

Thompson, C. E., Ball, S., Thompson, T. J. U. & Gowland, R. 2011: The abrasion of modern and archaeological bones by mobile sediments: the importance of transport modes. *Journal of Archaeological Science 38*, 784–793.

Villa, P. & Mahieu, E. 1991: Breakage patterns of human long bones. *Journal of Human Evolution 21*, 27–48.

Voorhies, M. 1969: Taphonomy and population dynamics of an early Pliocene vertebrate fauna, Knox country, Nebraska. *Contributions to Geology, Special Paper 1*, 69 pp. Department of Geology and Geophysics, University of Wyoming Press.

Yravedra, J. & Domínguez-Rodrigo, M. 2009: The shaft-based methodological approach to the quantification of long limb bones and its relevance to understanding hominin subsistence in the Pleistocene: application to four Paleolithic sites. *Journal of Quaternary Science 24*, 85–96.

Yravedra, J., Domínguez-Rodrigo, M., Santonja, M., Rubio-Jara, S., Panera, J., Pérez-González, A., Uribelarrea, D., Egeland, C., Mabulla, A. & Baquedano, E. 2016: The large mammal palimpsest from TK Thiongo korongo, Bed II Olduvai Gorge, Tanzania. *Quaternary International 417*, 3–15.

Supporting Information

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

Fig. S1. Handaxe used in the experimentation.

Table S1. Principal chemical and physical alterations affecting the FLKW fossil assemblage.

Table S2. Dry and green breakage patterns on the FLKW long bones.

Table S3. Distribution and description of FLKW tooth marks.

Data S1. Methods of 3D modelling of cut mark sections.

Sección III. II. Aplicación sobre el estudio de otros procesos tafonómicos

Artículo 8:

Título: **On Applications of Micro-photogrammetry and Geometric Morphometrics to Studies of Tooth Mark Morphology: the modern Olduvai Carnivore Site (Tanzania).**

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Resumen:

El cubil de carnívoros de Olduvai en la reciente publicación (Arriaza et al., 2016) se ha presentado como un yacimiento de gran importancia debido a que cuenta con una gran acumulación de huesos procesados por leones. Varios análisis tafonómicos independientes constataron que unos felinos de gran tamaño, es decir leones, en lugar de otro tipo de carnívoros, pudieron haber sido los responsables de la acumulación de más de 50 carcasas de ñu en el cubil de Olduvai (Arriaza et al., 2016). En el presente trabajo, se muestran los resultados obtenidos mediante la aplicación de técnicas micro-fotogramétricas y de morfometría geométrica en el estudio de los scores en los fósiles identificados en el cubil. Es la primera vez que esta técnica se aplica sobre fósiles óseos, dado su potencial para identificar los carnívoros involucrados en el consumo de canales y para establecer el orden de acceso. Los resultados muestran que tanto los leones como las hienas manchadas han modificado los huesos del cubil, corroborando las interpretaciones sugeridas en anteriores análisis tafonómicos y ecológicos de la guarida (Arriaza et al., 2016). Con este ejemplo mostramos que el uso de esta tecnología es muy efectiva a la hora de extraer gran cantidad de información tafonómica de cualquier conjunto de huesos modificados por carnívoros.

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On applications of micro-photogrammetry and geometric morphometrics to studies of tooth mark morphology: The modern Olduvai Carnivore Site (Tanzania)

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Recent application of photogrammetric and geometric morphometric approaches to the study of cut marks on bones has yielded positive results in discriminating different types of tools and even some raw materials. Here, we apply this analytical technique to the study of carnivore tooth scores. The goal is twofold: on the one hand, we intend to differentiate carnivore types and on the other one, we show the application of this approach to a sample of tooth scores from long bones documented at the modern assemblage of the Olduvai Carnivore Site (OCS). Previous taphonomic work at OCS suggested that this bone assemblage constituted a good evidence of a carcass accumulation behavior by lions, followed by hyena ravaging. The application of these 3D techniques to the selected sample of tooth marks shows that lions, as well as spotted hyenas, did indeed impart marks on the OCS assemblage. This reinforces the dual nature of the assemblage and the implication of lions in its formation.

1. Introduction

During the last decades a significant part of the research carried out in taphonomy has been focused on carnivore neotaphonomy. Bone assemblages created by spotted hyenas (*Crocuta crocuta*) have been intensively studied (e.g., Egeland et al., 2008; Kerbis Peterhans, 1990; Lam, 1992; Pickering, 2002; Sutcliffe, 1970). Additionally, controlled experiments have also been carried out simulating intervention in anthropogenic bone assemblages, in order to quantify the degree of post-depositional hyena ravaging after hyena consumption of part of the bones (Blumenschine, 1988; Domínguez-Rodrigo, 1997). Some features were proposed as typical characteristics of hyena bone assemblages (e.g., low abundance of compact bones, different age class profiles of the preys or abundance of carnivore remains) (Cruz-Uribe, 1991; Stiner, 1991). Subsequent studies have shown the great variability of this carnivore as taphonomic agent (Lam, 1992) and have revealed that only few criteria can be used to distinguish such bone assemblages (Pickering, 2002). Further research was carried out to understand the variability of the taphonomic signature among hyenid species (Egeland et al., 2008; Faith, 2007; Fourvel et al., 2015; Kuhn, 2011), taking into account that different ecological contexts can impact the outcome of the taphonomic property set of any given bone assemblage. These studies are crucial to create accurate analogues that serve to interpret archaeological assemblages.

Felids have also been targeted by neotaphonomic research. Leopards (*Panthera pardus*) have been proposed as potential bone accumulators in the savanna ecosystem (Brain, 1981; Kerbis Peterhans, 1990) and some interpretations consider felids as the primary accumulating agent of some of the early archaeological sites (Domínguez-Rodrigo et al., 2007). Research in modern savannas has analyzed the carcass consumption process at lion (*Panthera leo*) kills (Domínguez-Rodrigo, 1999; Gidna et al., 2014) and has provided descriptions of modern leopard dens (Brain, 1981; Ruiter and Berger, 2000).

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Despite the efforts made to determine the modifications that different carnivores leave on the bone assemblages, there is no consensus about an unequivocal feature that helps to discern the carnivore species involved and the access order. Sometimes, it is especially difficult because more than one species have been involved in the modification of the carcasses found at sites. Additionally, there is always some degree of equifinality, as documented through skeletal part representation or the tooth mark sizes generated by carnivore species with similar body mass (Andrés et al., 2012). Furthermore, neotaphonomic studies are subject to several shortcomings: the variables which quantify the skeletal part representation are diverse, results are not differentiated depending on body mass of the prey, sample size of the experiments is sometimes inadequate, the body mass of the prey in the experiments is not analogous to the ungulate size found at the sites, or experimental sets are based on the action of carnivores in captivity (Andrés et al., 2012; Gidna et al., 2013; Yravedra and Domínguez-Rodrigo, 2009).

Recently, new methods for analyzing classical taphonomic features have been proposed. Such methodology is primarily based on multivariate statistics. This is the case of the new term "taphotype" which integrates the differential quadrant bone destruction according to element type (Domínguez-Rodrigo et al., 2015). This method has proved that furrowing and tooth mark frequencies inflicted by several carnivores can be distinguished using multivariate statistics (Domínguez-Rodrigo et al., 2015). Moreover, the use of machine learning methods allows the distinction of skeletal part representations generated by felids from those seen in hyena dens (Arriaza and Domínguez-Rodrigo, 2016). That is also true when multivariate statistic is combined with the five-age class method for ungulate preys hunted by spotted hyenas and lions (Arriaza et al., 2015). Thus, multivariate approaches facilitate the identification of carnivores involved in the accumulation or modification of bone assemblages.

Other techniques that have recently been applied in neotaphonomy include geometric morphometric and micro-photogrammetric methods. Such techniques have been used for the analysis of cut (Maté-González et al., 2015, 2016) and tooth marks (scores), obtaining satisfactory results in order to differentiate scores produced by different carnivores (Muttart et al., 2016; Yravedra et al., submitted). Micro-photogrammetry affords three-dimensional high quality reconstructions, so that marks can be analyzed with high accuracy. Studies using three-dimensional reconstructions can be based on different techniques. Apart from the micro-photogrammetric approach (Maté-González et al., 2015, 2016), other researchers have worked with 3D digital microscopes (Boschin and Crezzini, 2012; Crezzini et al., 2014) or the Alicona 3D Infinite Focus Imaging microscope (Bello and Soligo, 2008; Bello et al., 2009; Bonney, 2014). In any case, these techniques have been employed in multiple contexts providing very useful results. For instance, such studies have succeeded in differentiating the raw materials used in the processing of carcasses (Boschin and Crezzini, 2012; Maté-González et al., 2016). They have also helped to interpret cannibalistic and funerary practices (Bello and Soligo, 2008; Bello et al., 2011a) as well as study teeth and the use of the mouth as a third hand (Bello et al., 2011b; Hillson et al., 2010). They contributed to the interpretation of engraved bones and antlers (Bello et al., 2013a) and the use of these materials as retouched tools and hammers (Abrams et al., 2014; Bello et al., 2013b) or for engraved pottery (Montani et al., 2012) and prehistoric art (Güth, 2012).

Recently a new modern bone assemblage – the Olduvai Carnivore Site (OCS) – has been presented as the first bone assemblage accumulated by lions (Arriaza et al., 2016). Several independent taphonomic analytic tools provided evidence that a large-size felid (namely, lions), rather than other types of carnivores, may have been responsible for the accumulation of more than 50 wildebeest carcasses at the OCS (Arriaza et al., 2016). In the present work, we show the results obtained by means of micro-photogrammetric and geometric morphometric techniques in the study of the scores identified at the OCS. It is the first time that such a technique is applied to this type of assemblages, given its potential utility to identify the carnivore(s) involved in the consumption of carcasses and to establish the access order. Our results show that both lions and spotted hyena have modified the OCS bones, corroborating the interpretations suggested in previous taphonomic and ecological analyses of the den (Arriaza et al., 2016). With this example we show that the use of this technology is an effective way of extracting further taphonomic information from any carnivore modified bone assemblage.

2. Material and methods

2.1. The Olduvai Carnivore Site (OCS)

During TOPPP's (The Olduvai Paleoanthropology and Paleoecology Project) 2012 field season in Olduvai Gorge (Tanzania), a modern carnivore site was found close to the third fault of the gorge (Fig. 1). The carnivore assemblage was located in the short grassland ecological unit of the Serengeti National Park. The OCS includes 55 wildebeest carcasses accumulated at least during 2 or more seasons. The skeletal part representation comprised 4533 bone specimens that belong to the same

Fig. 1. Location of the Olduvai Carnivore Site (OCS) (yellow star) and a wildebeest carcass found at the site. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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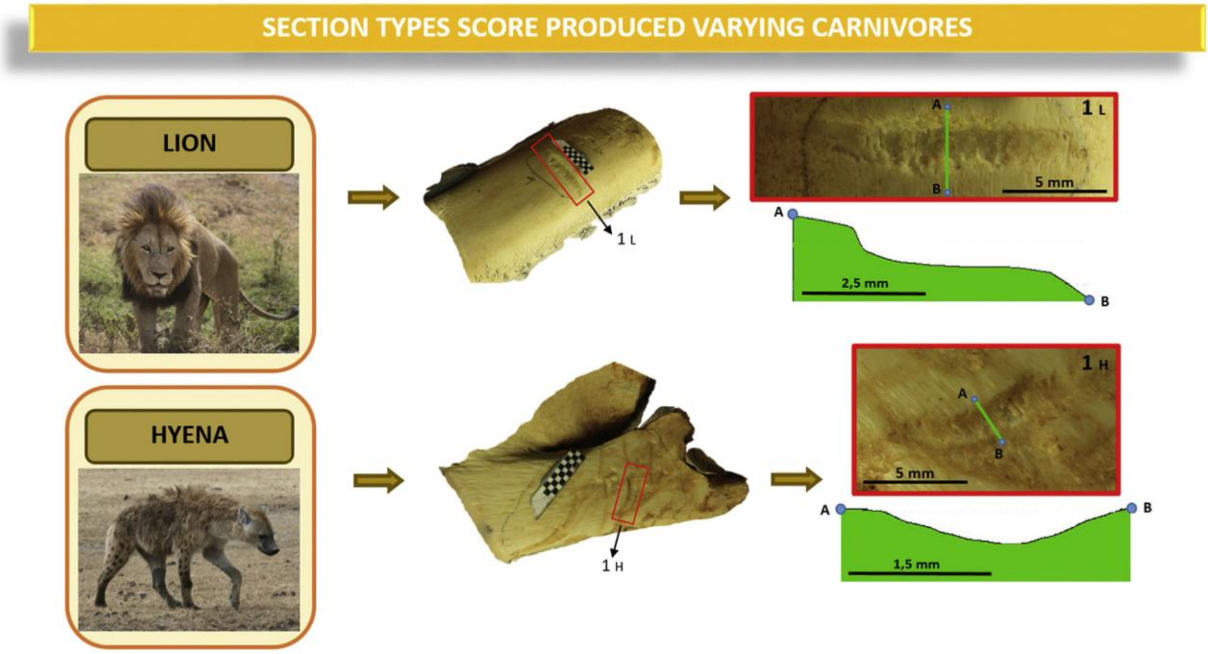

Fig. 2. Section types scores produced by the spotted hyena and lion.

species, the blue wildebeest (*Connochaetes taurinus*). Some of the carcasses were complete or almost complete. The taphonomic study carried out showed a low frequency of tooth marks, a low degree of bone breakage, and typical felid bone modifications on the axial skeleton and on the epiphyses. However, some long bones present bone destruction patterns carried out by a durophagus carnivore, such as those inflicted by spotted hyenas (Arriaza et al., 2016). The bone assemblage is dominated by young adults or mature adults, including only 5 yearlings (Arriaza et al., 2015). This data along with the high bone accumulation rate, the body mass of the prey, the prey specialization (only one ungulate species), and the behavioral ecology of the carnivores present in the short-grassland ecologic unit of the Serengeti, suggest that the primary accumulating agent was a felid, probably a nomad lion. However, spotted hyenas also modified the sample, scavenging part of the bones. The OCS may be the first documented bone assemblage accumulated by a lion. This constitutes a new framework for

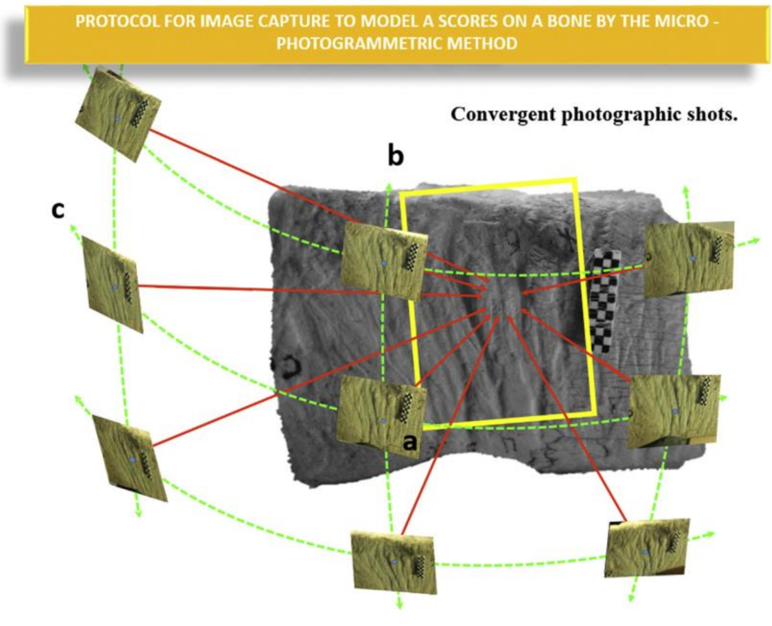

Fig. 3. Protocol for image capture to model a tooth mark on a bone by the micro-photogrammetric method, with convergent photographic shots. (a) Master and dependent images in central position, (b) vertical slave images, and (c) horizontal slave images.

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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

future taphonomic studies that is relevant for the interpretation of classical paleoanthropological sites such as those of Olduvai Gorge (Arriaza et al., 2016).

2.2. Material

Traditionally, the access order of the different kind of carnivores (felid versus hyenid) has been tested based on the frequency and the distribution of tooth marks on long bones. The focus on long bones is due to the fact that carnivore taphonomy has been developed primarily on these elements to test hominin-carnivore potential interactions in the formation of prehistoric bone assemblages (e.g., Blumenschine, 1988; Gidna et al., 2014) and long bones are usually the most frequent elements in most of the archaeological sites. Thus, 23 OCS long bones bearing tooth marks were selected for the present study aiming at differentiating tooth marks inflicted by lions and hyenas. The sample of study includes 1 ulna, 1 metacarpal, 5 femora, 4 tibiae, 6 humerus and 6 radii. For this study we have only analyzed tooth scores, since previous experimental analyses have demonstrated that scores are the only type of tooth marks that yield reliable results when trying to differentiate carnivore types (Yravedra et al., submitted). A total of 25 scores were selected randomly but on the basis of their preservation and general groove integrity. We excluded those scores that present a bad cortical preservation or some type of alteration, such as the appearance of biochemical modifications or exfoliation. Neither superficial nor inconspicuous tooth marks that provided a bad resolution when photographed stereographically have been selected for the study.

The experimental samples that we used to compare carnivore types and the OCS tooth score sample are from Cabárceno Reserve "Parque de la Naturaleza de Cabárceno", Cantabria (Northern Spain). For further detail on bone samples used in this work see Gidna et al. (2013) and Domínguez-Rodrigo et al. (2015). A total of 30 scores produced by lions on 12 adult equid long bone shafts and 33 hyena scores on 12 adult equid long bone shafts were analyzed (Yravedra et al., submitted). This sample is small and is presented here as a preliminary study given its clearly diagnostic value.

2.3. Methods

According to previous taphonomic analyses, the OCS tooth marks should have been made either by spotted hyenas or lions, or both (Arriaza et al., 2016). In this work, we tested this hypothesis using micro-photogrammetric and morphometric techniques.

High-resolution images were obtained through micro-photogrammetry and computer vision techniques and these were then used for the three-dimensional modeling of score sections (Fig. 2). Following the methodology of Maté-González et al. (2015), precise metrical models of scores were generated 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 lenses 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. Noise removal was not required since the protocol for data acquisition and the controlled environmental conditions guaranteed high-quality point clouds. The methodology required placing a millimetric scale next to the score 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 were treated with the photogrammetric reconstruction software GRAPHOS (inteGRAted PHOtogrammetric Suite) (Fig. 4) (González-Aguilera et al., 2016a, 2016b) 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.s 3 and 4).

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 30–35 min depending on the final number of photos taken.

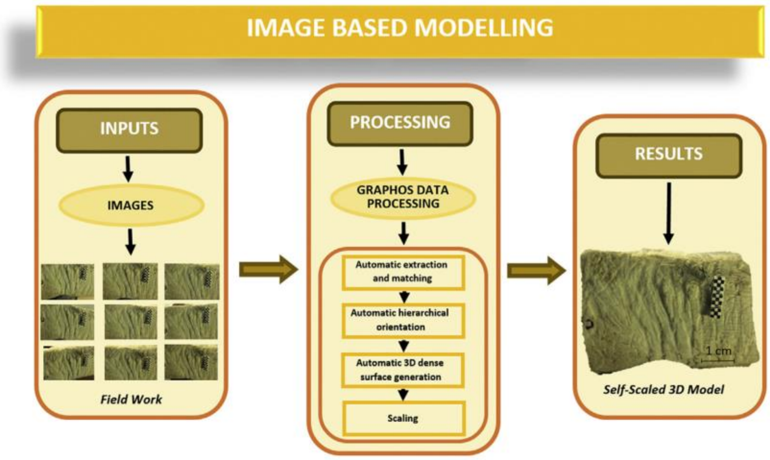

Fig. 4. Workflow of the image-based modeling technique.

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M.C. Arriaza et al. / Palaeogeography, Palaeoclimatology, Palaeoecology xxx (2017) xxx–xxx 5

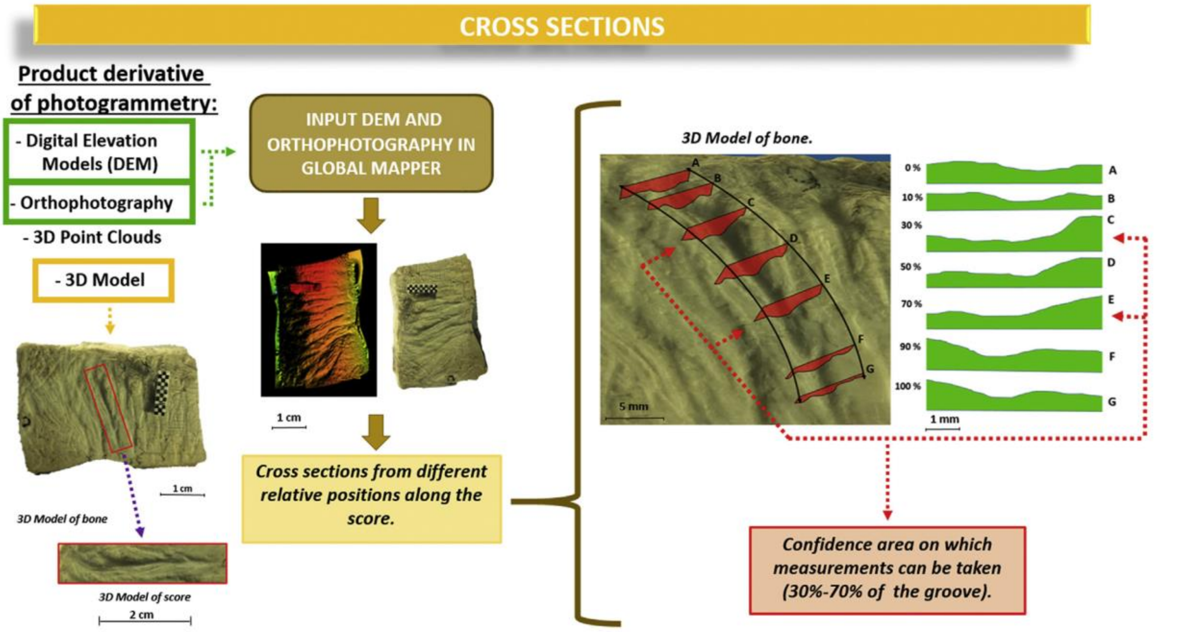

Fig. 5. Representation of the a–g sections of the tooth mark regarding its length.

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 (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 a geometric and statistical level.

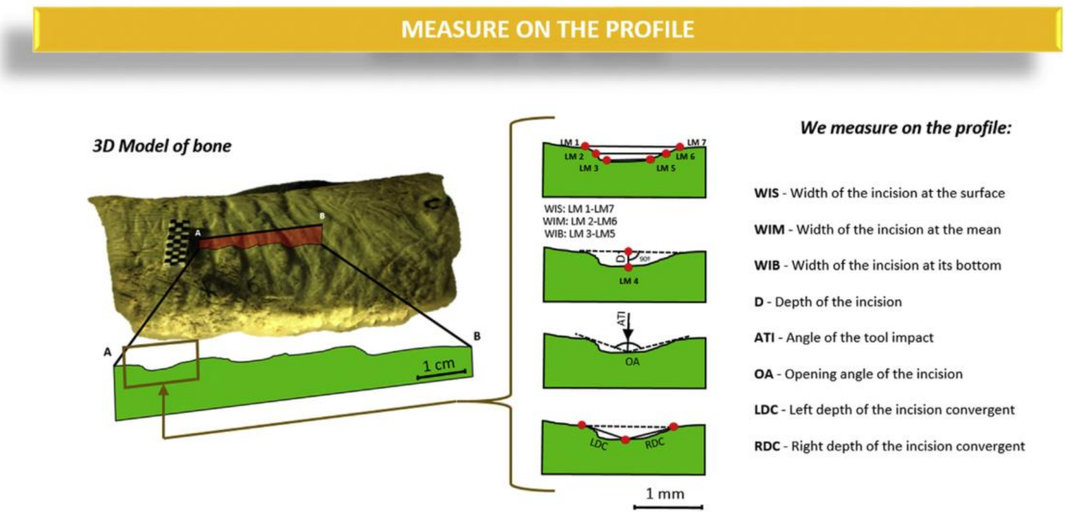

Fig. 6. Location of measurements sensu Bello et al. (2013a). Landmarks (LM1–7) used for the morphometric model are also represented.

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Table 2
Measurements taken on the profile.

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 of the incision	OA
Depth of the incision	D
Left depth of the incision convergent	LDC
Right depth of the incision convergent	RDC

Scores were measured at mid-length (about 50% of the mark length) as suggested in Maté-González et al. (2015). According to such description, for a confident comparison of scores, 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 WIS, WIM, WIB, OA, D, LDC, RDC (sensu Bello et al., 2013a) were taken on the mark section and used as quantitative variables (see Fig. 6 for measurements and Table 2).

The measurements for each score section were later compared using several statistical tests. In order to test if there was any difference in the several measurement of carnivores, a multivariate Principal Component Analysis (PCA) of the biometric data was performed with the library FactoMiner (Lê et al., 2008) in R (www.rproject.org) software (Core-Team, R, 2015). The PCA estimates mark similarities and differences on a bidimensional Euclidean space. In the present study we used the mark measurements transformed through scaling. Plotting of the PCA results with confidence ellipses was made with the ggplot2 R library.

A geometric morphometric analysis based on a Generalized Procrustes Analysis (GPA) was conducted as a supplementary alternative to the Multivariate Metric Analysis (Fig. 6). Such analyses use information captured in the form of homologous landmarks that describe each specimen independently. This technique takes the landmark data (coordinates) and normalizes the form information by the application of superimposition procedures. This involves the translation, rotation and scaling of shapes defined by landmark configurations. In this case, seven identical landmarks per section - as shown in Fig. 6 (LM1–7) - were considered from each mark. Landmarks were digitalized using tpsUtil (v. 1.60.) and tpsDig2 (v. 2.1.7), as explained in Maté-González et al. (2015). The location of the landmarks responded to the measures considered for the statistical analysis, as seen in Fig. 6. LandMark 1 (LM) 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; LM5, LM6 and LM7, in a opposed position to LM3, LM2 and LM1, respectively (Fig. 6). The resulting tps file was imported into R and analyzed using the "geomorph" library (Sherratt, 2014). Lastly, a Linear Discriminant Analysis (LDA) was performed to estimate the differences among the several groups of tooth marks. The LDA function included in the MASS R package was used.

A total of 88 high quality 3D models were generated with a reflex camera with a macro lens (average GSD (mm) = ±0.0078; average scaling error (mm) = ±0.0157; average photogrammetric error (mm) = ±0.0058; average precision (mm) = ±0.0168). This method fulfills the requirements of quick capture, automatic processing of images and high precision, so as to enable a precise and reliable statistical analysis.

It should be noted that 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), principal point (2) and distortion center (2), radial (3) and tangential (2) distortion, scaling and affinity factors (2)) (Fraser, 1980), was applied. This self-calibration is suitable and valid when we work with reflex cameras and some theoretical parameters are known.

3. Results

Statistical tests comparing the OCS score sections and those of the experimental sample from Cabárceno (Figs. 5 and 6) prove that there are certain features that allow the differentiation and identification of both, lions and hyenas, according to the way they score bone surfaces.

The PCA analysis shows that lion scores are clearly differentiated from those produced by hyenas (Fig. 7). Hyenas present a greater variability in the morphology of their scores, generating a certain overlap with lions. OCS scores are grouped into the ellipse corresponding to the lions (Fig. 7), being 68% of the marks directly associated with the lion ellipse (Table 3). The 32% remaining scores are grouped differently: 24% appear associated with hyena scores and 8% lie outside the range of variability described by both carnivores (marked with arrows in Fig. 7). This result is not surprising considering previous taphonomic analysis (Arriaza et al., 2016), where hyenas were described as secondary agents scavenging the carcasses after the primary consumption by lions. The PCA plot (Fig. 7) shows that most of the den scores match the lion sample.

On the other hand, the morphometric test described in Fig. 8 is more confusing: the scores produced by lions (in red) are grouped on the right of the plot, hyena scores (in black) lie on the left, while the OCS

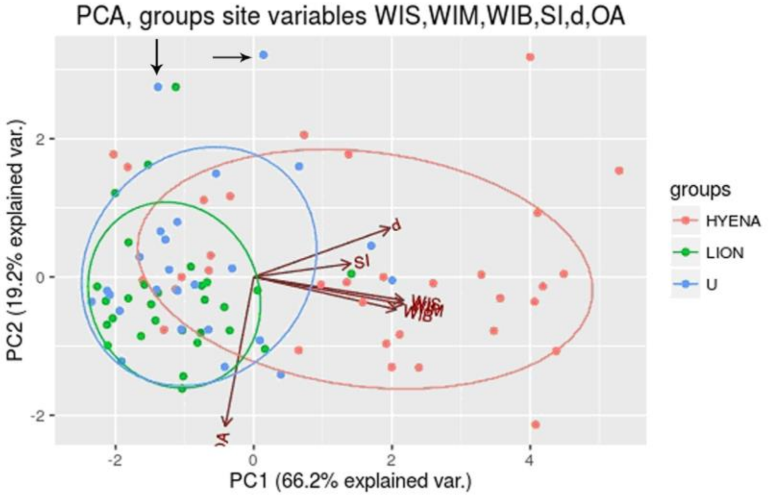

Fig. 7. PCA plot of the measurements indicated in Figs. 6 and 7. U refers to the OCS. Arrows indicate the scores that are outside the variability range of hyenas and lions.

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Table 3
LDA confusion matrices based on biometric data.

	Hyena	Lion
Hyena	28 (0.85)	5 (0.15)
Lion	2 (0.07)	27 (0.93)
OCS	8 (0.32)	17 (0.68)

marks (in green) occupy the whole graph. Comparative matrices do not provide conclusive results, since the OCS scores are placed between the lion and the hyena data (Table 4). This morphometric test is not conclusive and the degree of variation explained is lower than the one obtained with the biometric PCA (Fig. 8 vs Fig. 7).

Nevertheless, morphometric data suggest some morphological differences. Scores produced by lions are shallow and very wide with an open U-section, whereas hyena scores are deeper and their section is less open (Fig. 9).

In sum, the biometric test is more conclusive than the morphometric analysis. The biometric test and the corresponding confusion matrices (Fig. 7 and Table 3) show that a high percentage of the OCS scores were produced by lions, while hyenas exerted a minor and secondary impact on the assemblage. Bone accumulations produced by hyenas present a higher number of scores than pits, contrary to what happens in the samples primarily modified by lions (Domínguez-Rodrigo et al., 2012; Gidna et al., 2013, 2014). Most of the scores identified at the OCS describe the action of lions. If hyenas had been responsible for the OCS bone accumulation, the number of typical hyena scores would have been much higher than the amount of lion scores, which is not the case at the OCS. The morphometric test and its accuracy enhance the role hyenas might have played on the OCS accumulation (Fig. 8 and Table 4). Thus, our results agree that both lions and hyenas were involved in the consumption of the OCS assemblage. This confirms previously proposed hypothesis that suggested a primary access of lions to the wildebeest carcasses accumulated at OCS, and a subsequent intervention of the hyenas that would have scavenged some of the bones (Arriaza et al., 2016).

4. Discussion

The interaction of carnivores and hominins is a widely studied topic due to its great relevance in the understanding of the human evolutionary record. A very promising taphonomic variable concerns the tooth mark sizes generated by different carnivore species. This variable has been used to discuss bone assemblages as relevant as those from Sima de los Huesos or Olduvai Gorge (Andrews and Fernández-Jalvo, 1997; Selvaggio and Wilder, 2001; Domínguez-Rodrigo and Piqueras, 2003). According to Selvaggio and Wilder (2001), the mean tooth pit size on cancellous bone from the FLK Zinj was similar to the ones observed in the sample consumed by hyenas and lions. However, the results on the cortical bone suggested that the sample from the FLK Zinj was similar to samples generated by cheetah, leopard or hyenas (Selvaggio and Wilder, 2001). Based on these data, they argued that the last carnivore modifying the FLK Zinj bone assemblage was the hyena. Either hyenas were ravaging carcasses left by hominins, or felids firstly defleshed the carcasses, followed by hominins demarrowing them and hyenas ravaging the abandoned bones (Selvaggio and Wilder, 2001). Further research analyzed the same carnivore taxa studied by Selvaggio and Wilder (2001). The results revealed that tooth mark size also reached equifinality (Domínguez-Rodrigo and Piqueras, 2003). Several species showed overlapping pit sizes, although it was possible to differentiate between small-medium carnivores and larger species in accordance with tooth mark sizes on both cancellous and cortical bone sections (Domínguez-Rodrigo and Piqueras, 2003). The great variability suggested by tooth mark size analysis could not support the three-stage model hypothesis (carnivore-hominin-carnivore) for the FLK Zinj. Subsequently, other carnivorous and omnivorous species were studied such as the tiger, bobcat or caracal (Delaney-Rivera et al., 2009). The body mass of the taxa and the bone portion where the tooth mark was inflicted may determine the tooth mark dimensions (Delaney-Rivera et al., 2009). Again, an overlap between different species was identified but small and large carnivores inflicted differentiable tooth pits on cortical bone (shafts). It was argued that this variable alone was not a good indicator of the carnivore species involved in the exploitation of fossil

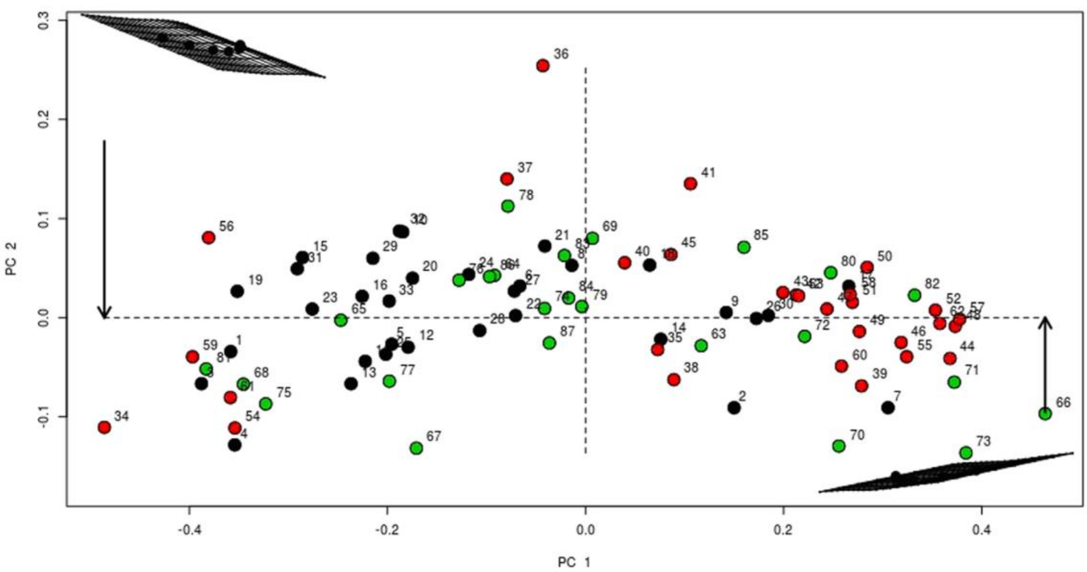

Fig. 8. PCA plot where the morphometric data of the OCS scores are compared with the experimental sample. Black: hyena, Red: lion, Green: OCS. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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Table 4
LDA confusion matrices based on morphometric data.

	Hyena	Lion
Hyena	25 (0.76)	8 (0.24)
Lion	7 (0.24)	22 (0.76)
OCS	14 (0.56)	11 (024)

assemblages (Delaney-Rivera et al., 2009). Recently, new studies have shown that the inadequate sample size of the experiments may create the overlap between taxa, in addition to the differential carnivore body mass and age (Andrés et al., 2012). Furthermore, some experiments have been made using the same prey for all the carnivore species involved, regardless of the body mass of the carnivore. Nevertheless, carnivore body mass normally constrains the selection of preys in wild environments (Andrés et al., 2012). Combining a larger sample and taking into account the prey size usually consumed by the different carnivore taxa, it is possible to differentiate the species according to the tooth marks inflicted on long bone shafts (Andrés et al., 2012). However, more taphonomic variables should be analyzed in order to develop solid hypotheses concerning the implication of carnivores in fossil assemblages (Delaney-Rivera et al., 2009; Andrés et al., 2012).

During the last few years, new methodologies have been proposed to analyze the action of carnivores: taphotypes, skeletal part representation combined with machine learning methods or age profiles (five-age class method) classified through multivariate statistic may differentiate the taxa involved in the bone modification (Domínguez-Rodrigo et al., 2015; Arriaza et al., 2015; Arriaza and Domínguez-Rodrigo, 2016). Moreover, micro-photogrametry and geometric morphometry have been applied in taphonomic studies (Maté-González et al., 2015, 2016). These techniques can reproduce three-dimensional models of the marks identified on bones facilitating its morphologic study. This has already been done to analyze the raw material used in the processing of carcasses (Maté-González et al., 2016). Although tooth mark dimensions alone cannot distinguish between carnivore taxa, the morphology of the tooth marks seems to be different depending on the carnivore species (Yravedra et al., submitted). A recent study carried out with bones consumed by spotted hyenas, lions, wolves, foxes and jaguars showed that the scores inflicted on the shafts by these carnivores can be differentiated when the tooth mark is reconstructed through micro-photogrammetry and analyzed using geometric morphometrics (Yravedra et al., submitted).

Here, the samples created by spotted hyenas and lions were compared with the tooth marks from the OCS, in order to test previous taphonomic hypotheses that argued that the bone assemblage was primary consumed by the lion followed by the hyena ravaging. The statistical analyses showed that the OCS score morphology is similar to the one created by lions and spotted hyenas in controlled experiments. The scores are located on the shafts, which means that both carnivores generated tooth marks on this bone portion. Lions usually deflesh carcasses in the consumption process of the prey and may inflict tooth marks on the shafts of long bones during the consumption of flesh (Domínguez-Rodrigo, 1999; Gidna et al., 2014). Hyenas usually break long bones to access the bone marrow and grease (Sutcliffe, 1970). The scores which are morphologically similar to those inflicted by the spotted hyena may correspond to the secondary access to the carcasses by this durophagus carnivore. In sum, our morphometric analyses support the hypothesis raised previously through the taphonomic and the ecologic analyses. In spite of the low number of tooth marks analyzed from the OCS the hypothesis raised through the morphometric analysis meets the one proposed from a taphonomic and ecological point of view. The neotaphonomic collection contains spotted hyena, lion, fox, jaguar and wolf samples (Yravedra et al., submitted). Another relevant species that has been proposed as an accumulating agent in the African savanna is the leopard (Brain, 1981; Kerbis Peterhans, 1990; Ruiter and Berger, 2000). The morphometric analysis of the leopard tooth marks should be compared with the tooth marks inflicted by hyenids and other large felids such as the lion. Equally, jackals, which are usually the first bone modification agent in simulated archaeological sites in the African savanna (work in progress), should be compared to wild dogs (although this species does not modify bones greatly (Yravedra et al., 2014)).

The morphometric analyses of tooth marks may constitute a new research line in carnivore taphonomy and may be of great value in the study of paleoanthropological sites. High-resolution morphologic studies such as the one presented here may help determine the species involved in the bone modification of bone assemblages.

5. Conclusions and future perspectives

Recent morphometric studies of tooth marks successfully distinguished different carnivore species. This work presents a new methodology that opens up new and interesting perspectives for the identification of taphonomic processes. The application of photogrammetry for the modeling of two- or three-dimensional reconstructions in combination with the application of geometric morphometrics and multivariate statistics allows the examination of new horizons in taphonomy. In some recent works, these techniques have been applied to the study of cut marks, but this new methodology has the potential to also analyze other taphonomic marks such as trampling or biochemical alterations.

These new techniques have been used in the bone assemblage from the OCS to test the hypothesis that emerged from previous taphonomic analyses that the site resulted from a lion-hyena model. The results show that both hyenas and lions inflicted tooth marks on the long bones from the OCS. Thus, this variable supports that the bone assemblage was firstly consumed by lions and hyenas subsequently scavenged part of the remains. This constitutes a new framework where lions should be considered potential bone accumulators in the past. It is for this reason that the morphometric analysis of tooth marks may help in the taphonomic study of paleoanthropological sites.

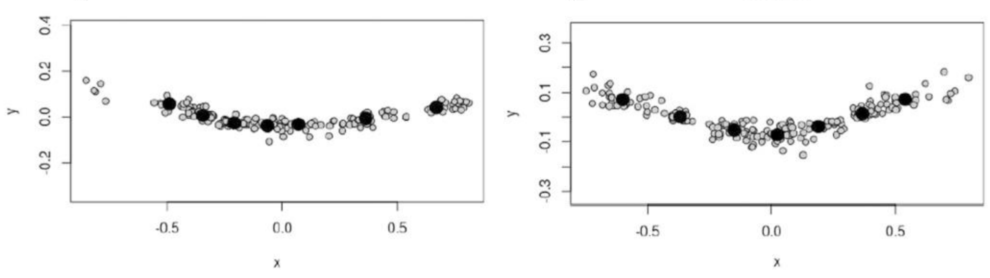

Fig. 9. GPA test including the profiles of the carnivore scores analyzed, where a: lion, b: hyena.

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Regarding future perspectives, graphical tests based on QQ-plots and robust estimators such as the median and the median absolute deviation would be desirable to check the reliability of data, especially if they do not follow a Gaussian distribution. Another important aspect for future works involves the automatic recognition of coded targets, so that 3D models can be automatically scaled, guaranteeing subpixel precision.

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References

Abrams, G., Bello, S.M., Di Modica, K., Pirson, S., Bonjean, D., 2014. When Neanderthals used cave bear (*Ursus spelaeus*) remains: bone retouchers from unit 5 of Scladina Cave (Belgium). Quat. Int. 326–327, 274–287.

Andrés, M., Gidna, A., Yravedra, J., Domínguez-Rodrigo, M., 2012. A study of dimensional differences of tooth marks (pits and scores) on bones modified by small and large carnivores. Archaeol. Anthropol. Sci. 4, 209–219.

Andrews, P., Fernández-Jalvo, Y., 1997. Surface modifications of the Sima de los Huesos fossil humans. J. Hum. Evol. 33, 191–217.

Arriaza, M.C., Domínguez-Rodrigo, M., 2016. When felids and hominins ruled at Olduvai Gorge: a machine learning analysis of the skeletal profiles of the non-anthropogenic bed I sites. Quat. Sci. Rev. 139, 43–52.

Arriaza, M.C., Domínguez-Rodrigo, M., Martínez-Maza, C., Mabulla, A., Baquedano, E., 2015. Differential predation by age and sex classes in blue wildebeest in Serengeti: study of a modern carnivore den in Olduvai Gorge (Tanzania). PLoS One 10 (5), e0125944. http://dx.doi.org/10.1371/journal.pone.0125944.

Arriaza, M.C., Domínguez-Rodrigo, M., Yravedra, J., Baquedano, 2016. Lions as bone accumulators? Paleontological and ecological implications of a modern bone assemblage from Olduvai Gorge. PLoS One 11 (5), e0153797. http://dx.doi.org/10.1371/journal.pone.0153797.

Bello, S.M., Soligo, C., 2008. A new method for the quantitative analysis of cutmark micromorphology. J. Archaeol. Sci. 35, 1542–1552.

Bello, S.M., Parfitt, S.A., Stringer, C.B., 2009. Quantitative micromorphological analyses of cut marks produced by ancient and modern handaxes. J. Archaeol. Sci. 36, 1869–1880.

Bello, S.M., Parfitt, S.A., Stringer, C.B., 2011a. Earliest directly-dated human skullcups. PLoS One 6 (2), e17026. http://dx.doi.org/10.1371/journal.pone.0017026.

Bello, S.M., Verveniotou, E., Cornish, L., Parfitt, S.A., 2011b. Dimensional microscope analysis of bone and tooth surface modifications: comparisons of fossil specimens and replicas. Scanning 33, 316–324.

Bello, S.M., De Groote, I., Delbarre, G., 2013a. 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.

Bello, S.M., Parfitt, S.A., Groote, I., Kennaway, G., 2013b. Investigating experimental knapping damage on an antler hammer: a pilot-study using high-resolution imaging and analytical techniques. J. Archaeol. Sci. 40, 4528–4537.

Blumenschine, R.J., 1988. An experimental model of the timing of hominid and carnivore influence on archaeological bone assemblages. J. Archaeol. Sci. 15, 483–502.

Bonney, H., 2014. An investigation of the use of discriminant analysis for the classification of blade edge type from cut marks made by metal and bamboo blades. Am. J. Phys. Anthropol. 154, 575–584.

Boschin, F., Crezzini, J., 2012. Morphometrical analysis on cut marks using a 3D digital microscope. Int. J. Osteoarchaeol. 22, 549–562.

Brain, C.K., 1981. Hunters or the Hunted? An Introduction to African Cave Taphonomy. University of Chicago Press, Chicago.

Core-Team, R, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria URL. https://www.Rproject.org/.

Crezzini, J., Boschin, F., Wierer, U., Boscato, P., 2014. Wild cats and cut marks: exploitation of *Felis silvestris* in the Mesolithic of Galgenbühel/Dos de la Forca (South Tyrol, Italy). Quat. Int. 330, 52–60.

Cruz-Uribe, K., 1991. Distinguishing hyaena from hominid bone accumulations. J. Field Archaeol. 18, 467–486.

Delaney-Rivera, C., Plummer, T.W., Hodgson, J.A., Forrest, F., Hertel, F., Oliver, J.S., 2009. Pits and pitfalls: taxonomic variability and patterning in tooth mark dimensions. J. Archaeol. Sci. 36, 2597–2608.

Domínguez-Rodrigo, M., 1997. Meat-eating by early hominids at the FLK 22 Zinjanthropus site, Olduvai Gorge, Tanzania: an experimental approach using cut mark data. J. Hum. Evol. 33, 669–690.

Domínguez-Rodrigo, M., 1999. Flesh availability and bone modification in carcasses consumed by lions. Palaeogeogr. Palaeoclimatol. Palaeoecol. 149, 373–388.

Domínguez-Rodrigo, M., Piqueras, A., 2003. The use of tooth pits to identify carnivore taxa in tooth-marked archaeofaunas and their relevance to reconstruct hominid carcass processing behaviours. J. Archaeol. Sci. 30, 1385–1391.

Domínguez-Rodrigo, M., Barba, R., Egeland, C., 2007. Deconstructing Olduvai: A Taphonomic Study of the Bed I Sites. Springer, New York.

Domínguez-Rodrigo, M., Gidna, A., Yravedra, J., Musiba, C., 2012. A comparativeneotaphonomic study of felids, hyenids and canids: an analogical framework based on long bone modification patterns. J. Taphon. 10, 147–164.

Domínguez-Rodrigo, M., Yravedra, J., Organista, E., Gidna, A., Fourvel, J.B., Baquedano, E., 2015. A new methodology approach to the taphonomic study of paleontological and archaeological faunal assemblages: a preliminary case study from Olduvai Gorge (Tanzania). J. Archaeol. Sci. 59, 35–53.

Egeland, A., Egeland, C.P., Bunn, H.T., 2008. Taphonomic analysis of a modern spotted hyena (*Crocuta crocuta*) den from Nairobi, Kenya. J. Taphonomy. 6, 275–299.

Faith, J.T., 2007. Sources of variation in carnivore tooth-mark frequencies in a modern spotted hyena (*Crocuta crocuta*) den assemblage, Amboseli Park, Kenya. J. Archaeol. Sci. 34 (10), 1601–1609.

Fourvel, J.P., Fosse, P., Avery, G., 2015. Spotted, striped or brown? Taphonomic studies at dens of extant hyaenas in eastern and southern Africa. Quat. Int. 369, 38–50.

Fraser, C., 1980. Multiple focal setting self-calibration of close-range metric cameras. Photogramm. Eng. Remote. Sens. 46, 1161–1171.

Gidna, A., Yravedra, J., Domínguez Rodrigo, M., 2013. A cautionary note on the use of captive carnivores to model wild predator behavior: a comparison of bone modification patterns on long bones by captive and wild lions. J. Archaeol. Sci. 40, 1903–1910.

Gidna, A.O., Kisui, B., Musiba, C., Mabulla, A., Domínguez-Rodrigo, M., 2014. An ecological neotaphonomic study of carcass consumption by lions in Tarangire National Park (Tanzania) and its evidence for human evolutionary biology. Quat. Int. 322–323, 167–180.

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).

Güth, A., 2012. Using 3D scanning in the investigation of Upper Palaeolithic engravings: results of a pilot study. J. Archaeol. Sci. 39 (10), 3105–3114.

Hillson, S., Parfitt, S.A., Bello, S.M., Roberts, M.B., Stringer, C.B., 2010. Two hominin incisor teeth from the Middle Pleistocene site of Boxgrove, Sussex, England. J. Hum. Evol. 59, 493–503.

Kerbis Peterhans, J., 1990. The Roles of Porcupines, Leopard and Hyenas in Ungulate Carcass Dispersal: Implications for Paleoanthropology. Ph.D. dissertation. University of Chicago.

Kuhn, B., 2011. Hyaenids: Taphonomy and Implications for the Palaeoenvironment. Cambridge Scholars, Newcastle upon Tyne.

Lam, Y.M., 1992. Variability in the behaviour of spotted hyaenas as taphonomic agents. J. Archaeol. Sci. 19, 389–406.

Lê, S., Josse, J., Husson, F., 2008. FactoMineR: an r package for multivariate analysis. J. Stat. Softw. 25 (1), 1–18.

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, J.F., Domínguez-Rodrigo, M., 2015. Micro-photogrammetric characterization of cut marks on bones. J. Archaeol. Sci. 62, 128–142.

Maté-González, M.A., Palomeque-González, J.F., 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. Archaeol. Anthropol. Sci. http://dx.doi.org/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 (11), 3349–3353.

Muttart, M., Pante, M., Njau, J., 2016. Quantifying taxonomic distinctions in tooth mark morphology with high-resolution 3D scanning. Abstracts of the Paleoanthropology Society 2016 Meeting. PaleoAnthropology A1–A34.

Pickering, T., 2002. Reconsideration of criteria for differentiating faunal assemblages accumulated by hyenas and hominids. Int. J. Osteoarchaeol. 12, 127–141.

Ruiter, D., Berger, L., 2000. Leopards as taphonomic agents in dolomitic caves – implications for bone accumulations in the hominid-bearing deposits of South Africa. J. Archaeol. Sci. 27, 665–684.

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Selvaggio, M.M., Wilder, J., 2001. Identifying the involvement of multiple carnivore taxon with archaeological bone assemblages. J. Archaeol. Sci. 28, 465–470.
Sherratt, E., 2014. Quick Guide to Geomorph v. 2.0. http://www.public.iastate.edu/~dcadams/PDFPubs/Quick%20Guide%20to%20Geomorph%20v2.0.pdf.
Stiner, M.C., 1991. Food procurement and transport by human and non-human predators. J. Archaeol. Sci. 18, 455–482.
Sutcliffe, A., 1970. Spotted hyaena: crusher, gnawer, digester and collector of bones. Nature 227, 1110–1113.
Yravedra, J., Domínguez-Rodrigo, M., 2009. The shaft-based methodological approach to the quantification of long limb bones and its relevance to understanding hominin subsistence in the Pleistocene: application to four Paleolithic sites. J. Quat. Sci. 24, 85–96.
Yravedra, J., Andrés, M., Domínguez-Rodrigo, M., 2014. A taphonomic study of the African wild dog (*Lycaon pictus*). Archaeol. Anthropol. Sci. 6, 113–124.
Yravedra J. García-Vargas E.Maté-González M.A. Palomeque-González J.F. The use of micro-photogrammetic and geometric-morphometry for identifying carnivore activity in the bone assemblages, J Archaeol Sci: Report (submitted)

Please cite this article as: Arriaza, M.C., et al., On applications of micro-photogrammetry and geometric morphometrics to studies of tooth mark morphology: The modern Olduvai Carniv..., Palaeogeogr. Palaeoclimatol. Palaeoecol. (2017), http://dx.doi.org/10.1016/j.palaeo.2017.01.036

Sección IV: Conclusiones

IV. I. Conclusiones sobre la metodología desarrollada para el estudio de marcas de corte

El objetivo principal de esta Tesis Doctoral es generar una metodología de bajo coste que nos permita realizar un estudio en detalle de las marcas de corte en hueso, suficientemente precisa como para igualar los resultados de equipos microscópicos más costosos y al alcance de muy pocos investigadores. El fin de dicha metodología debe permitir identificar el tipo de materia prima utilizado para el aprovechamiento cárnico en un yacimiento, con el objetivo de poder ayudar a entender los procesos económicos empleados por los grupos humanos del pasado.

Para conseguir dicho propósito se han explorado y testeado técnicas microscópicas, técnicas fotográficas, técnicas laser y técnicas micro-fotogramétricas combinadas todas ellas con la visión computacional.

Sobre la **metodología desarrollada** para el estudio de marcas de corte en hueso, podemos extraer las siguientes conclusiones:

- *Técnica fotogramétrica múltiple convergente*. Esta técnica genera muy buenos resultados en la reconstrucción tridimensional de marcas de corte. Esto se debe principalmente a que las técnicas fotogramétricas convergentes ofrecen muy buena geometría de intersección de haces perspectivos junto con una mayor redundancia y solape entre las imágenes, lo que favorece la aplicación de los modernos algoritmos de la fotogrametría de última generación (González-Aguilera et al., 2016a, b).

- *Fotografías realizadas con una cámara réflex y un objetivo macro previamente calibrado o auto-calibrado*. Garantizar la calidad en los modelos 3D resultantes pasa por disponer del conocimiento (calibración y/o auto-calibración) de los parámetros internos tanto geométricos como físicos del sistema fotográfico.

- *GRAPHOS como software Open Source de reconstrucción fotogramétrico*. Dada la complejidad y variabilidad de los objetos a analizar en esta Tesis Doctoral, el software libre GRAPHOS (URL) permite utilizar diferentes algoritmos en cada una de las fases del proceso fotogramétrico (González-Aguilera et al., 2016a, b), ajustándose mejor el proceso a las características que requiera un objeto concreto.

- *PANDORA como herramienta de análisis morfométrico y estadístico*. Con el objetivo de poder identificar el tipo de materia prima utilizada en el aprovechamiento cárnico a través de los modelos 3D de marcas de corte, se ha desarrollado el software PANDORA. Dicho software es capaz de caracterizar y discriminar las marcas de corte en relación con la materia prima utilizada atendiendo a sus dimensiones y morfología (e.g. profundidad, anchura, longitud, sección, morfología, perfil, simetría de ángulos, etc.).

El resultado del estudio demuestra que el método micro-fotogramétrico que se basa en la fotografía múltiple oblicua y que usa una cámara réflex con objetivo macro auto-calibrado junto con el procedimiento fotogramétrico encapsulado en el software GRAPHOS y el análisis morfométrico y estadístico encapsulado en el software PANDORA, es el que depara en todos los casos de estudio analizados los mejores resultados, ajustándose a las precisiones y a unos tiempos relativamente cortos en la captura y post-procesamiento de los datos.

Con idea de reforzar estas conclusiones, en esta Tesis Doctoral se ha realizado un estudio comparativo entre la metodología desarrollada basada en la micro-fotogrametría (Micro-Photogrammetry - M-PG) con otras dos técnicas consolidadas que se utilizan actualmente para realizar el estudio de marcas de corte en hueso: Three-dimensional Digital Microscope (3DM) y Laser Scanning Confocal Microscopy (LSCM) (Maté-González et al., 2017a).

Sobre el **estudio comparativo** de las diferentes técnicas analizadas, se deducen las siguientes conclusiones:

- Las tres técnicas empleadas (M-PG, 3DM y LSCM) presentan resultados similares y son por lo tanto igualmente válidas para la realización de los análisis métricos y morfométricos de las marcas de corte en hueso. Esta conclusión viene avalada por un estudio estadístico.

- La metodología desarrollada y apoyada en la técnica M-PG cumple con los estándares de calidad exigidos a las técnicas más costosas y tecnológicamente más sofisticadas para la realización de los estudios tafonómicos de las marcas de corte en hueso. Los promedios de resolución y precisión conseguidos están en 8 y 17 micras, respectivamente.

- La técnica M-PG requiere de un mayor tiempo de captura de datos (e.g. 25 minutos) frente a las técnicas microscópicas (< 1 minuto).

- La técnica M-PG no llega a la resolución suficiente como para documentar adecuadamente marcas inconspícuas o alteraciones más superficiales como el trampling, las cuales si pueden ser estudiadas con técnicas microscópicas.

- La técnica M-PG presenta más sencillez, flexibilidad (posibilidad de transportar y de trabajar directamente en yacimientos o museos) y bajo coste frente a las técnicas microscópicas.

- Asimismo, la compatibilidad de los métodos fotogramétricos y microscópicos y la posibilidad de producir modelos tridimensionales de alta resolución comparables entre cualquiera de ellos, facilita el intercambio de información entre equipos de investigación, generando una gran perspectiva de futuro para estos análisis.

IV. II. Conclusiones sobre el estudio de las marcas de corte

Sobre los **resultados experimentales de laboratorio sobre las marcas de corte en hueso** obtenemos las siguientes conclusiones:

- Para el análisis de las marcas de corte en hueso utilizamos secciones entre el 30 y 70 % de las marcas. Estadísticamente se ha comprobado que las secciones comprendidas en ese intervalo, son morfológicamente similares y por lo tanto son representativas de la marca.

- El análisis tridimensional de las marcas de corte - con independencia de la metodología seguida, ya sea mediante reconstrucción micro-fotogramétrica (Maté-González et al., 2015, 2016, Palomeque-González et al., 2017) u otros procedimientos (Bartelink et al., 2001, Bello y Soligo, 2008, Bello et al., 2009, 2013, 2015, Boschin y Crezzini, 2012 entre otros) - permite analizar desde perspectivas más completas dichas marcas, posibilitando identificarlas y caracterizarlas mucho mejor que con las técnicas bidimensionales.

- Teniendo en cuenta las posibilidades analíticas que ofrecen los análisis tridimensionales de las marcas de corte y atendiendo a las conclusiones que se han observado en los trabajos anteriores (Maté-González et al., 2016a, b, 2017b; Palomeque-González et al., 2017; Yravedra et al., 2017a), los estudios morfométricos de dichas marcas, son más resolutivos que los análisis biométricos.

- Es posible diferenciar las materias primas con las que se realizan las marcas de corte. En este caso se han diferenciado marcas de corte de metal, sílex, basalto, cuarcita de Olduvai y cuarcita de la Península Ibérica. No obstante, el solapamiento de algunas marcas de corte nos indica que para aplicar la metodología propuesta al estudio de estas en yacimientos arqueológicos, es preferible disponer de muestras más amplias, ya que desde el punto de vista estadístico los resultados obtenidos son más fiables que si utilizamos menor cantidad de muestras.

En relación a la aplicación de los **estudios de las marcas de corte en yacimientos arqueológicos**, obtenemos las siguientes conclusiones:

- El 81% de las marcas de corte del yacimiento Bell’s Korongo (BK) (Tanzania) se realizaron con útiles de cuarcita del Naibor Soit, lo que nos permite sugerir que las diversas actividades realizadas están relacionadas con el aprovechamiento cárnico de las carcasas utilizando técnicas como la descarnación o la desarticulación. Con lo cual se confirman los estudios líticos realizados con anterioridad sobre el yacimiento de BK, constatando que la cuarcita es la materia prima predominante en dicho yacimiento (Leakey, 1971, Hay, 1976, Kyara, 1999, Díez et al., 1999a, b). De esta forma se observa en la investigación realizada una correlación positiva entre la fauna y las materias primas con las que se fabricaron las herramientas líticas de BK.

- Los análisis fotogramétricos y morfométricos de las marcas de corte realizados en el yacimiento FLK-WEST (Frida Leakey Korongo) (Tanzania), constatan que las marcas de corte encontradas en los fósiles del yacimiento fueron realizadas con lascas de cuarcita en lugar de con bifaces también llamados hachas de mano.

- La metodología desarrollada en esta Tesis Doctoral es válida para diferenciar, in situ, las materias primas con las que se producen las marcas de corte en un yacimiento arqueológico (BK). También es posible diferenciar la herramienta con la que se realizan dichas marcas, lascas *vs* bifaces (FLK-WEST).

IV. III. Conclusiones sobre los estudios realizados en marcas de diente

La nueva metodología que hemos desarrollado en la presente Tesis Doctoral y que nos ha resultado válida para el estudio de las marcas de corte, también resulta válida para estudiar marcas realizadas en huesos por dientes de animales (scores). En relación a la **aplicación de los estudios de las marcas de diente en yacimientos arqueológicos-paleontológicos**, podemos extraer las siguientes conclusiones:

- Los resultados obtenidos de la aplicación de las técnicas micro-fotogramétricas y de la morfometría geométrica en el estudio realizado sobre los scores en los fósiles identificados en el yacimiento Cubil de Olduvai (Tanzania), muestran que tanto los leones como las hienas manchadas han intervenido sobre los huesos que aparecen en dicho lugar, siendo la acción de los leones mayoritaria, corroborando las interpretaciones sugeridas en anteriores análisis tafonómicos y ecológicos de la guarida (Arriaza et al., 2016). De esta información podemos concluir que los leones han intervenido en este yacimiento primeramente y a continuación lo han hecho las hienas, apoyando la interpretación de Arriaza et al., (2016).

Sección V: Perspectivas futuras

Tras realizar los trabajos de investigación desarrollados durante esta Tesis Doctoral se abren nuevas líneas de investigación y mejoras para complementar y optimizar los estudios vinculados al estudio de las marcas que aparecen en los restos fósiles:

V. I. Metodología

Como ya hemos dicho, la metodología desarrollada y apoyada en las técnicas micro-fotogramétricas cumple con los estándares de calidad exigidos a las técnicas más costosas y tecnológicamente más sofisticadas para la realización de los estudios tafonómicos de las marcas de corte en hueso. El principal problema de las técnicas micro-fotogramétricas respecto a las técnicas microscópicas, es el tiempo de captura y procesamiento de los datos. Mientras que con las técnicas micro-fotogramétricas se tardan veinticinco minutos aproximadamente, con las técnicas microscópicas se tarda menos de un minuto.

De unos años a esta parte (cuando se comenzó la Tesis Doctoral) los avances en el campo de la fotogrametría han experimentado un gran desarrollo gracias a la creación de nuevos algoritmos matemáticos provenientes de la visión computacional, propiciando una estabilidad y robustez a los métodos numéricos fotogramétricos. El desarrollo de software y hardware en el ámbito informático, la fotografía digital, el procesamiento digital de imágenes junto con los algoritmos que utiliza la visión computacional que integra los métodos numéricos fotogramétricos de rango cercano, también han permitido automatizar varios de los procesos del flujo fotogramétrico. Todos estos avancen han repercutido positivamente en la reducción de los tiempos de procesado. Seguramente en los próximos años los avances en el campo de la fotogrametría sigan reduciendo los tiempos de procesado.

Los avances de las técnicas láser se han centrado más en la mejora de las precisiones. Cuando se comenzó esta Tesis Doctoral se probaron y testaron varios sistemas láser para la documentación de marcas de corte en hueso. Los resultados obtenidos no fueron resolutivos. En la actualidad con las mejoras tecnológicas, estamos probando y testando un nuevo equipo que se basa en las técnica láser de la luz estructurada que en una primera fase experimental permite obtener modelos 3D con resoluciones similares a las técnicas micro-fotogramétricas y en tiempos parecidos a los de los microscopios (> 1 minuto). Al ser igualmente efectiva que las técnicas micro-fotogramétricas, la única ventaja que podemos destacar es que permita ganar velocidad en la reconstrucción de los modelos 3D (al ser un sensor activo). En cuanto a costes, las técnicas laser por lo general siguen siendo bastante más costosas económicamente que la utilización de metodologías fotogramétricas (cámara + software).

Asimismo, la compatibilidad de los métodos fotogramétricos y microscópicos y la posibilidad de producir modelos tridimensionales de alta resolución comparables entre cualquiera de ellos, facilita el intercambio de información entre equipos de investigación, generando una gran perspectiva de futuro para estos análisis. Como consecuencia, sería posible llevar a cabo proyectos tafonómicos integrados para evaluar la variabilidad de las marcas de corte basadas en diferentes variables, como el tamaño de los animales (Bello et al., 2013), la materia prima (Maté-González et al., 2016a, b; Yravedra et al., 2017a), o el tipo de herramienta (Galán y Domínguez-Rodrigo, 2013; Yravedra et al., 2017b) independientemente de la técnica utilizada. Algunos estudios a lo largo de esta línea de investigación ya están publicados (Bello y Soligo, 2008, Bello, 2011; Bello et al., 2013, 2015) y podrían sentar las bases de futuros análisis, integrando diversas técnicas; e.g. Alicone 3D (Bello y Soligo, 2008; Bello, 2011; Bello et al., 2013), ESEM (Bello et al., 2015, Blasco et al., 2016) M-PG (Maté-González et al., 2016a, b; Yravedra et al., 2017a, b) y LSCM (Archer and Braun, 2013).

V. II. Marcas de corte.

De los dos estudios experimentales realizados, en el primero de ellos (Maté-González et al., 2016a, b), existe un solapamiento de las marcas de corte realizadas con basalto y sílex. En el segundo (Maté-González et al., 2017), existen diferencias significativas entre las marcas de corte de cuarcitas de la Península Ibérica y Tanzania. Este tipo de cuarcitas tienen diferente tipo de grano. Esto nos hace plantearnos si el grano que compone la materia prima, puede intervenir en el proceso de corte. Por estos motivos, es necesario realizar análisis para comprender mejor la morfología de las marcas de corte, como:

- Comprobar qué condiciona más en una marca de corte, la materia prima, o el grano de la materia prima.
- Comprobar si existe coincidencia entre dos marcas de corte realizadas con materias primas diferentes en las que su grano es similar.

Se ha observado que para la identificación y caracterización de las marcas de corte en hueso, los análisis morfométricos son más resolutivos que los estrictamente biométricos. No obstante, el solapamiento de algunas marcas de corte nos indica que para aplicar la metodología propuesta al estudio de estas en yacimientos arqueológicos, es preferible disponer de muestras más amplias, ya que desde el punto de vista estadístico los resultados obtenidos son más fiables que si utilizamos muestras pequeñas.

Por otra parte esta Tesis Doctoral es el comienzo de la aplicación de una nueva metodología con un gran potencial de desarrollo, que puede hacer posible la utilización de nuevas técnicas de análisis estadísticos y morfométricos tridimensionales para comprobar si se obtiene una mejora de los resultados. Con esta nueva metodología sería interesante comparar las marcas experimentales desarrolladas por nosotros: lascas simples de sílex (de la Península Ibérica y de Tanzania), lascas simples de cuarcita (de la Península Ibérica y de Tanzania), lascas simples de basalto (de Tanzania) y bifaces de cuarcita (Tanzania). Estos experimentos se podrían cmpletar incluyendo lascas retocadas de sílex y de cuarcita tanto de la Península Ibérica como de Tanzania, así como de otros lugares.

Respecto a las muestras realizadas por nosotros en los experimentos de la presente investigación, las marcas de corte se han llevado a cabo en casi todos los casos sobre las diáfisis de los huesos largos. El motivo de realizar los experimentos sobre las diáfisis se debe a que en los yacimientos arqueológicos las marcas de corte aparecen sobre dichas partes óseas en las piezas fósiles. La principal razón, es porque los paquetes musculares de los animales se asientan sobre dichas diáfisis. Futuros trabajos de investigación irían encauzados a estudiar las marcas de corte atendiendo a la biometría, morfología, etc., para constatar si las marcas de corte situadas en las diáfisis son o no diferentes de las que se sitúan en extremos articulares o en huesos axiales. Sin embargo, a la hora de comprobar si en un yacimiento arqueológico se utiliza una materia prima u otra para realizar actividades de procesado, no es necesario realizar tal análisis experimental, ya que en nuestro caso hemos trabajado sobre las mismas partes que aparecen en los yacimientos con marcas de corte. Así tanto en FLK-West como en BK las marcas analizadas se sitúan sobre las diáfisis, lo que se corresponde con los experimentos que hemos realizado. La diferenciación entre marcas de corte producidas en diáfisis, epífisis o elementos axiales sería otro tipo de trabajo experimental destinado a responder a otras cuestiones como por ejemplo ver cómo cambian las características de la marca en función de la sección anatómica procesada.

Otras líneas de investigación podrían ir dirigidas a comprobar cómo afecta la curvatura del hueso a la marcas de corte y determinar si hay diferencias importantes entre las marcas de cortes producidas en distintos huesos. Del mismo modo podemos preguntarnos si la actividad generada deja similares o distintas marcas de corte, por ejemplo como se diferencian las marcas asociadas a la descarnación frente las relacionadas con la desarticulación. Estas y otras cuestiones podrían ser futuras líneas de investigación que podrían tener su aplicación en el estudio de ciertos yacimientos arqueológicos.

Por el contrario tiene más sentido experimentar cómo cambian las marcas de corte atendiendo a los atributos morfológicos, biométricos, etc., estudiando otro tipo de variables como por ejemplo el tamaño de las carcasas. ¿Las marcas de corte son iguales sobre el hueso de un búfalo, de un elefante, de una oveja o de un conejo? Esta pregunta marcaría una seria línea de investigación que se puede relacionar con el tipo de materias primas con las que se procesan las carcasas en un yacimiento arqueológico.

Otra sería constatar si se diferencian las marcas de corte sobre un individuo en su etapa infantil o en su etapa adulta. En dichos individuos la textura del hueso es diferente y quizá esto podría afectar a la morfología de marca de corte realizada sobre el hueso. No obstante el protocolo a seguir en estos experimentos no es sencillo, ya que esto implica hacer varios experimentos con distintas materias primas, contrastar las diferentes variables y valorar cómo condicionan o repercuten sobre las marcas de corte. En todo caso son trabajos por desarrollar y marcan lo que podrían ser investigaciones futuras.

Hasta ahora nos hemos centrado en el tipo de materia prima con el que se realizan las marcas de corte sobre hueso porque es una variable que se puede comparar con lo que aparece en el yacimiento y porque aporta información relevante en la interpretación económica de este, no sólo en lo que afecta a la explotación de los recursos cárnicos en cuanto a las materias primas empleadas, sino también porque permiten valorar como se gestionan las materias primas y las herramientas en el yacimiento. Por ejemplo, en BK se han encontrado lascas de cuarcita y también lascas de basalto, sin embargo estas parecen no haber sido utilizadas en el procesamiento de las carcasas. Lo mismo ocurre en FLKW respecto a los bifaces. Es posible que basaltos y bifaces se utilizaran en cada yacimiento para actividades diferentes. Análisis preliminares parecen indicar que en FLKW los bifaces se utilizaron para explotar vegetales (Mercader com. Pers.).

Las técnicas que venimos desarrollando e incrementando pueden aplicarse a otras líneas de investigación como la diferenciación de marcas de corte respecto a otros procesos naturales que pueden generar trazas parecidas a las marcas de corte (e.g. trampling). Dichas marcas pueden tener grandes repercusiones interpretativas en lo que respecta a los orígenes del comportamiento humano. Quizá un análisis tridimensional de las marcas apoyado por un análisis morfométrico geométrico permitiría zanjar la polémica que existe sobre si las marcas que aparecen en el yacimiento de Dikika son marcas de corte (McPherron et al., 2011; Thompson et al., 2015) o por el contrario no lo son (Domínguez Rodrigo et al., 2010, 2011, 2012).

Otras cuestiones que pueden ser analizadas en otro tipo de contextos son:

- Comprobar si la alteración térmica de los huesos afecta o no a las características de las marcas de corte. También se pueden realizar estudios que puedan diferenciar si las marcas de corte se producen antes o después del cocinado del hueso. Es decir, ¿cambia la morfología de la marca si la carne se cocina?, en caso de tener resultados positivos, esto nos permitiría saber en qué momento se comienza a cocinar la carne.
- Estudiar cómo cambian las características de las marcas en función de si la carcasa está o no congelada. Por ejemplo en contextos glaciares podría permitirnos ver el momento estacional en el que se procesa una carcasa, ya que en ciertos ámbitos, durante las gélidas estaciones invernales las carcasas podrían estar congeladas, a diferencia de las estaciones más benignas.

IV. IV. Marcas de diente

En la investigación realizada en Arriaza et al., (2017) sobre el Cubil de Olduvai (Tanzania), se demuestra que tanto los leones como las hienas manchadas han intervenido sobre los huesos que aparecen en dicho lugar, siendo la acción de los leones mayoritaria, corroborando las interpretaciones sugeridas en anteriores análisis tafonómicos y ecológicos de la guarida (Arriaza et al., 2016).

Sería muy interesante aumentar la muestra de carnívoros teniendo en cuenta una serie de consideraciones, como por ejemplo seleccionar carnívoros que compartan nichos ecológicos. De esta manera la metodología desarrollada se podría aplicar en contextos arqueológicos y paleontológicos. En este trabajo ya hemos realizado un análisis con dos carnívoros que comparten el mismo hábitat, los leones y las hienas, y hemos comprobado que es posible distinguirlos a través de sus scores. Sería interesante realizar un estudio similar a este, comparando scores de lobo con oso, jaguar con puma, león con leopardo y hiena, etc.

También tenemos que tener en cuenta que este trabajo se ha realizado con animales que se encuentran en condiciones de cautividad, por lo que puede ser interesante verificar los resultados obtenidos empleando una muestra representativa de animales salvajes. Es probable que dado que nos fijamos sólo en la forma de la marca de diente el estado en el que los animales viven (cautividad o salvaje) no afecte a los resultados obtenidos.

Este estudio abre la posibilidad de realizar análisis futuros que permitan una identificación fiable basada en el análisis de marcas de diente, un paso más allá de las obras anteriores (Selvaggio y Wilder, 2001; Domínguez-Rodrigo y Piqueras, 2003; Delaney-Rivera et al., 2009; Andrés et al., 2012). Un ejemplo sería la aplicación de esta técnica para intentar diferenciar tipos de carnívoro a través de otras marcas de dientes como son los pits. Los pits han sido descritos como las marcas de dientes más representativas para la identificación de los carnívoros (Selvaggio y Wilder, 2001; Domínguez-Rodrigo y Piqueras, 2003; Delaney-Rivera et al., 2009; Andrés et al., 2012), aunque también han mostrado un grado importante de equifinalidad entre carnívoros grandes y carnívoros pequeños. No obstante nuestro estudio abre la puerta a investigaciones futuras sobre estudios estadísticos y morfométricos tridimensionales de scores y / o pits. Sería interesante comprobar si los análisis estadísticos y morfométricos en 3D de los scores son más resolutivos que los realizados en 2D.

También sería muy interesante realizar un estudio comparativo entre marcas de pits y marcas de percusión, ya que en ocasiones es muy complejo diferenciarlas en especial cuando las marcas de percusión se producen con percutor no modificado, así en dos estudios experimentales se ha mostrado que las marcas de percusión no pueden diferenciarse de las marcas de diente en el 30% de los casos (Galán et al 2009; Pickering y Egeland 2006).

Referencias bibliográficas

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.

Andrés, M., Gidna, A., Yravedra, J. & Domínguez-Rodrigo, M. (2012). A study of dimensional differences of tooth marks (pits and scores) on bones modified by small and large carnivores. Archaeol. Anthropol. Sci.4, 209–219.

Archer, W. & Braun, D. R. (2013). Investigating the signature of aquatic resource use within Pleistocene hominin dietary adaptations. PloS one, 8(8), e69899.

Arriaza, M. C., Domínguez-Rodrigo, M., Yravedra, J. & Baquedano, E. (2016). Lions as bone accumulators? Paleontological and ecological implications of a modern bone assemblage from Olduvai Gorge. PLoS One 11 (5), e0153797. http://dx.doi.org/10.1371/journal.pone.0153797.

Arriaza, M. C., Yravedra, J., Domínguez-Rodrigo, M., Maté-González, M. Á., García Vargas, E., Palomeque-González, J. F., Aramendi, J., González-Aguilera, D. & Baquedano, E. (2017). On Applications of Micro-photogrammetry and Geometric Morphometrics to Studies of Tooth Mark Morphology: the modern Olduvai Carnivore Site (Tanzania). Palaeogeography, Palaeoclimatology, Palaeoecology, DOI: 10.1016/j.palaeo.2017.01.036.

Ballester, A. M. C. & Lillo, J. A. L. (2012). Registro tridimensional acumulativo de la secuencia estratigráfica. Fotogrametría y SIG en la intervención arqueológica de lo Boligni (Alacant). Virtual Archaeology Review, 3(5), 81-88.

Bartelink, E. J., Wiersema, J. M. & Demaree, R. S. (2001). Quantitative analysis of sharp-force trauma: An application of scanning electron microscopy in forensic anthropology. Journal of Forensic Sciences 46, 1288–1293.

Baxter, M (2003). Statistics in Archaeology. Arnold, New York.

Bello, S. M. (2011). New Results from the Examination of Cut-Marks Using Three-Dimensional Imaging. In: Ashton, N., Lewis, S.G., Stringer, C. (Eds.): The Ancient Human Occupation of Britain, Amsterdam: The Netherlands, 249-262.

Bello, S. M. & Soligo, C. (2008). A new method for the quantitative analysis of cutmark micromorphology. Journal of Archaeological Science 35, 1542–1552.

Bello, S. M., Parfitt, S. A. & Stringer, C. B. (2009). Quantitative micromorphological analyses of cut marks produced by ancient and modern handaxes. Journal of Archaeological Science 36, 1869–1880.

Bello, S. M., 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. Journal of Archaeological Science 40, 2464-2476.

Bello, S. M., Saladié, P., Cáceres, I., Rodríguez-Hidalgo, A. & Parfitt, S. A. (2015). Upper Palaeolithic ritualistic cannibalism: Gough's Cave (Somerset, UK) from head to toe. Journal of Human Evolution 82, 170-189.

Binford, L. R. (1981). Bones: Ancient Men, Modern Myths. New York, Academic press.

Blasco, R. (2008). Human consumption of tortoises at Level IV of Bolomor Cave Valencia, Spain. Journal of Archaeological Science 35, 2839-2848.

Blasco, R. & Fernández Peris, J. (2009). Middle Pleistocene bird consumption at Level XI of Bolomor Cave Valencia, Spain. Journal of Archaeological Science 36, 2213-2223.

Blasco, R. & Fernández Peris, J. (2012). A uniquely broad spectrum diet during the Middle Pleistocene at Bolomor Cave, Valencia, Spain. Quaternary International 252, 16-31.

Blasco, R., Rosell, J., Smith, K. T., Maul, L. C., Sañudo, P., Barkai, R. & Gopher, A. (2016). Tortoises as a dietary supplement: A view from the Middle Pleistocene site of Qesem Cave, Israel. Quaternary Science Reviews, 133, 165-182.

Bonney, H. (2014). An Investigation of the Use of Discriminant Analysis for the Classification of Blade Edge Type From Cut Marks Made by Metal and Bamboo Blades. American Journal of Physical Anthropology 154, 575-584.

Boschin, F. & Crezzini, J. (2012). Morphometrical Analysis on Cut Marks Using a 3D Digital Microscope. International Journal of Osteoarchaeology 22, 549–562.

Brain, C. K. (1981): The Hunters or the Hunted. An Introduction to African Cave Taphonomy. Chicago: University of Chicago Press.

Bunn, H. T. (1982). Meat eating and human evolution: Studies on the diet and subsistence patterns of Plio-Pleistocene hominids in East Africa. Ph. D. Dissertation, University of California, Berkeley.

Bunn, H. T. (1983). Comparative analysis of modern bone assemblages from a Sam hunter-gatherer camp in a Kalahari Desert Bostwana, and from Spotted hyaena den near Nairobi, Kenya. En Clutton-Brock, J. & Grigson C. (eds): Anaimals and Archaeology vol. 1. Hunters and their Prey. Brittish Archaeological Reports International Series 163. 143-148 Oxford.

Calvache, A. T. M., García, J. L. P., Colmenero, V. B. & Arenas, A. L. (2011). Estudio geométrico de piezas arqueológicas a partir de un modelo virtual 3D. Virtual Archaeology Review, 2(3), 109-113.

Cano, P., Lamolda, F., Torres, J. C. & del Mar Villafranca, M. (2010). Uso de escáner láser 3D para el registro del estado previo a la intervención de la Fuente de los Leones de La Alhambra. Virtual Archaeology Review, 1(2), 89-94. http://polipapers.upv.es/index.php/var/article/view/4695/4833.

Capaldo, S. D. (1997). Experimental determinations of carcass proceding by Plio-Pleistocene hominids and carnivores at FLK 22 (Zinjanthropus), Olduvai Gorge, Tanzania. Journal of Human Evolution 33, 555-598.

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.

Cobo, E. P., Vaz, P. M., Labrado, E. O., Zamora, Á. I. & Granero, A. B. M. (2012). Proyecto de musealización de los restos hallados en la estación de Ópera (Metro de Madrid). Reconstrucciones infográficas, escaneo laser 3D y digitalización del patrimonio arqueológico. Virtual Archaeology Review, 3(6), 88-92.

Coder, P. O. & del Pino Espinosa, B. (2013). Digitalización 3D automática con láser escáner, fotogrametría y videogrametría. El caso práctico del Templo de Diana (Mérida). Virtual Archaeology Review, 4(8), 90-94.

Cruzado, J. C. & Jiménez, F. J. S. (2016). Recontrucción virtual del Molino de la Tapada. In Nuevas estrategias en la gestión del Patrimonio Industrial. I Congreso Internacional de Patrimonio Industrial y de la Obra Pública (pp. 160-171). Fundación Patrimonio Industrial de Andalucía.

De Heinzelin, J., Clark, J. D., White, T., Hart, W., Renne, P., Wolde Gabriel, G., Beyene, Y. & Vrba, E. (1999). Environment and behavior of 2.5–million–year-old Bouri hominids. Science 284, 625-629.

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.

Defleur, A., White, T., Valensi, P., Slimak, L. & Crégut-Bonnoure, E. (1999) Neanderthal cannibalism at Moula-Guercy, Ardèche, France. Science 286, 128-131.

Delaney-Rivera, C., Plummer, T. W., Hodgson, J. A., Forrest, F., Hertel, F. & Oliver, J.S. (2009). Pits and pitfalls: taxonomic variability and patterning in tooth mark dimensions. J. Archaeol. Sci. 36, 2597–2608.

Del Pozo, S., Herrero-Pascual, J., Felipe-García, B., Hernández-López, D., Rodríguez-Gonzálvez, P. & González-Aguilera, D. (2016). Multispectral Radiometric Analysis of Façades to Detect Pathologies from Active and Passive Remote Sensing. Remote Sensing, 8(1), 80.

Díez, C., Fernández Jalvo, Y., Rossells, J. & Cáceres, I. (1999a). Zooarchaeology and taphonomy of Aurora stratum (Gran Dolina, Sierra de Atapuerca, Spain.). Journal of Human Evolution. Vol 37-Nº3/4. Pag 623-652.

Díez, C., Moreno, V., Rodríguez, J., Rosell, J. & Cáceres, I. (1999b). Estudio arqueozoológico de los restos de macrovertebrados de la Unidad III de galería. En Atapuerca. Ocupaciones humanas y paleoecológicas del Yacimiento de Galería. Arqueología de Castilla y León. (ed.) Carbonell, E.; Rosas González, A. & Díez, J. C. (1999). 265-281.

Domínguez-Rodrigo, M. (1997). Meat eating by early homids at FLK Zinj 22 Site, Olduvay Gorge Tanzania: An experimental a roach using cut-mark data. Journal of Human Evolution 33, 669-690.

Domínguez-Rodrigo, M. & Piqueras, A. (2003). The use of tooth pits to identify carnivore taxa in tooth-marked archaeofaunas and their relevance to reconstruct hominid carcass processing behaviours. J. Archaeol. Sci. 30, 1385–1391.

Domínguez-Rodrigo, M. & Yravedra, J. (2009). Why are cut mark frequencies in archaeofaunal assemblages so variable? A multivariate analysis. Journal of Archaeological Science36, Issue 3, March 2009, Pages 884-894.

Domínguez-Rodrigo, M., de la Torre, I., Luque, L., Alcalá, L., Mora, R., Serrallonga, J. & Medina, V. (2002). The ST Site Complex at Peninj, West Lake Natron, Tanzania:

Implications for Early Hominid Behavioural Models. Journal of Archaeological Science 29, 639 - 665.

Domínguez-Rodrigo, M., Pickering, T. R., Semaw, S. & Rogers, M. (2005). Cutmarked bones from archaeological sites at Gona, Afar, Ethiopia: Implications for the function of the world's oldest stone tools. Journal of Human Evolution 48, 109-121.

Domínguez-Rodrigo, M., Barba, R. & Egeland, C.P. (2007). Deconstructing Olduvai. Springer, New York.

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

Domínguez-Rodrigo, M., Pickering, T. R. & Bunn, H. T. (2010). Configurational approach to identifying the earliest hominin butchers. Proceedings of the National Academy of Sciences USA 107 (49), 20929–20934.

Domínguez-Rodrigo, M., Pickering, T. R. & Bunn, H. T. (2011). Reply to McPherron et al.,: Doubting Dikika is about data, not paradigms. Proc. Natl. Acad. Sci. 108, 117-117.

Domínguez-Rodrigo, M., Pickering, T. R. & Bunn, H. T. (2012). Experimental study of cut marks made with rocks unmodified by human flaking and its bearing on claims of 3.4 million-year-old butchery evidence from Dikika, Ethiopia. Journal of Archaeological Science 39, 205–214.

Domínguez-Rodrigo, M., Bunn, H. T. & Yravedra, J. (2014). A critical re-evaluation of bone surface modification models for inferring fossil hominin and carnivore interactions through a multivariate approach: application to the FLK Zinj archaeofaunal assemblage (Olduvai Gorge, Tanzania). Quaternary International 322-23, 32-43.

Efremov, L. A. (1940). Taphonomy a new branch of Paleontology Pan.American Geologist 74 (2) 81-93.

Falkingham, P. L. (2012). Acquisition of high resolution three-dimensional models using free, open-source, photogrammetric software. Palaeontologia electronica, 15(1), 15.

Farjas Abadía, M., Díaz Moreno, M. Á., Crespo Fraguas, Á., Ruíz Serrano, C., Martínez Pardo-Gil, G., Alfonso Carbajosa, E., Pereira Sieso, J., Isabel Ludeña, S & Castillo Bargueño, I. D. (2015). Aplicación de nuevas tecnologías en la Arqueología de la Guerra Civil Española: Los Yesares, Pinto (Madrid. Application of new technologies in archeology of the Civil War: The Yesares, Pinto (Madrid. Virtual Archaeology Review, 6(12), 122-136.

Fellner, D. W., Havemann, S., Beckmann, P. & Pan, X. (2011). Practical 3D Reconstruction of Cultural Heritage Artefacts from Photographs–Potentials and Issues. Virtual Archaeology Review, 2(4), 95-103.

Fernández Martínez, V. M. (2015). Arqueo-estadística: métodos cuantitativos en arqueología. Alianza, Madrid.

Fernández, F. L. (2016). Rescate documental de petroglifos y reconstrucción 3d del corredor Dolménico de Cubillejo de Lara, Burgos. In Virtual Archaeology Review (Vol. 7, No. 14, pp. 43-52). Universitat Politècnica de València.

Fernández-Jalvo, Y., Díez, J. C., Bermúdez de Castro, J. M., Carbonell, E. & Arsuaga, J. (1996). Evidence of early cannibalism. Science 271, 277-278.

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

Finlayson, C., Brown, K., Blasco, R., Rosell, J. & Negro, J. (2012). Birds of a feather: Neanderthal exploitation of raptors and corvids. PLoS One 79 45927.

Fisher, D. C. (1995). Bone surface modifications in zooarchaeology. Journal of Archaeological Method and Theory 2. 7-68.

Förstner, W. & Wrobel, B. P. (2016). Photogrammetric Computer Vision. Springer. ISBN 978-3-319-11550-4.

Galán, A. B., Rodríguez, M., de Juana, S. & Domínguez-Rodrigo, M. (2009) A new experimental study on percussion marks and notches and their bearing on the interpretation of hammerstone-broken faunal assemblages. Journal of Archaeological Science, 36, 776–84.

Galán, A. B. & Domínguez-Rodrigo, M. (2013). An experimental study of the Anatomical distribution of cut marks created by filletng and disarticulation on the long bone ends. Archeometry 55, 6. 1132-1149.

García, J. L. P., Calvache, A. T. M., Escarcena, F. J. C. & Arenas, A. L. (2011). Fotogrametría de bajo coste para la modelización de edificios históricos. Virtual Archaeology Review, 2(3), 121-125.

García-Morales, R. M. & Cortina, M. L. (2015). Paleocatálogo 3D: Photogrammetry for the realization of a high quality, accessible and free 3D Virtual Catalog. Virtual Archaeology Review, 6(13), 35-40. http://polipapers.upv.es/index.php/var/article/view/4369/4497.

García-Morales, R. M., Cortina, M. L., Pintado, J. A. & Novella, L. R. (2015). Princeps Resurgens: archaeological research and photogrammetric documentation in the study of a Roman thoracata statue of Los Bañales (Uncastillo, Zaragoza). Virtual Archaeology Review, 6(13), 65-71. http://polipapers.upv.es/index.php/var/article/view/4379/4505.

Giacoboni, G. & Patou Mathis, M. (2002). Fiche ra els taphonomiques en Cahier X, retochoirs, Compresseurs, percuteurs os a impresicions et eraillures fiches de la commision de nomenclature sur le industrie de l'os prehistorique ed Auguste et al., edic. soc Pre Franç.

Gifford, D. P. (1981). "Taphonomy and Paleoecology: A critique review of Archaeology's sister disciplines" en Schiffer, M (ed). Advances in Archaeological Method and Theory 4. Academic Press Orlando 77-101.

Gil, D. R., Rubio, J. M., Preysler, J. B., Martín, J. J. F. & Codes, J. F. (2010). Nuevos métodos para viejas tecnologías: análisis y documentación de los materiales arqueológicos mediante la aplicación de sistemas Láser-scanner 3D. Virtual Archaeology Review, 1(1), 169-173.

Gilbert, W. H. & Richards, G. D. (2000). Digital imaging of bone and tooth modification. The Anatomical Record 261, 237–246.

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.

Gower, J. C. (1975). Generalized procrustes analysis. Psychometrika, 40, 33-51.

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. Journal of the Israel Prehistoric Society 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.

Guidi, G., Russo, M., Ercoli, S., Remondino, F., Rizzi, A. & Menna, F. (2009). A multi-resolution methodology for the 3D modeling of large and complex archeological areas. International Journal of Architectural Computing, 7(1), 39-55.

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.

Haynes, G. A. (1980). Bone modification and skeletal disturbances by natural agencies: studies in North America. University Microfilms International. The Catholic University of America. PH D.

Huguet, R. (2007). Primeras ocupaciones humanas en la Península Ibérica: paleoeconomía en la Sierra de Atapuerca (Burgos) y la cuenca de Guadix-Baza (Granada) durante el pleistoceno inferior. Tesis Doctoral. Universitat Rovira i Virgili.

Jones, P. R. (1980). Experimental butchery whith modern stone tools and its relevance for Palaeolithic archaeology. World Archaeology 12 (2) 153-165.

Kotoula, E. & Kyranoudi, M. (2013). Study of ancient greek and roman coins using reflectance transformation imaging. E-Conservation Magazine, 25, 74-88.

Kyara, O. A. (1999). Lithic raw materials and their implications on assemblage variation and hominid behavior during Bed II, Olduvai Gorge, Tanzania. Unpublished Ph.D., University of Rutgers, New Brunswick.

Lartet, E. (1860). On the coexistence of man with Certain extinct quadrupeds, proved by fossil bones from various Pleistocene deposits, bearing incisions made by sharp instruments. Quarterly Journal of the sociological society of London 16, 471-479.

Lartet, E. & Christy, H. (1875). Reliquiae Acquitanicae being contributions to the Archaeology and Paleontology of Perigord and adjoining provinces of Southern France. London Willians and Nagorte.

Leakey, M. D. (1971). Olduvai Gorge. Vol 3. Excavations in Beds I and II, 1960-1963. Cambridge, Cambridge University Press.

López, M. S., González, A. U., Pajas, J. A. & Martínez-Bea, M. (2010). Documentación sistémica del arte rupestre mediante el análisis espectral del escaneado 3D de las estaciones pintadas en Aragón, El caso concreto del abrigo de La Vacada (Castellote, Teruel) y el covacho del Plano del Pulido (Caspe, Zaragoza). España. Virtual Archaeology Review, 1(1), 123-127.

Lyman, R. L. (1987). Archaeofaunas and butchery studies: a taphonomic perspective. En Schiffer, M. (ed). Advances in Archaeological Method and Theory, 10 249-337. New York.

Marín-Monfort, M. D., Pesquero, M. D. & Fernández-Jalvo, Y. (2014). Compressive marks from gravel substrate on vertebrate remains: a preliminary experimental study. Quaternary International, Volume 330, 30, 118-125.

Martin, H. (1909). Desarticulation des quelques regions chez les rumiants et le cheval a l'epoque mousterienne. Bulletin de la Societé Préhistorique Françcaise 7, 303-310.

Martin, H. (1907-10). Recherches sur l'evolution du Musterien dans le gisement de la Quina (Charente). Vol. Industrie Osseuse. Paris Schleicher Freres.

Maté-González, M. Á., Yravedra, J., González-Aguilera, D., Palomeque-González, J. F. & Domínguez-Rodrigo, M. (2015). Micro-photogrammetric characterization of cut marks on bones. Journal of Archaeological Science 62, 128-142. DOI: 10.1016/j.jas.2015.08.006.

Maté-González, M. Á., Palomeque-González, J.F., Yravedra, J., Domínguez-Rodrigo, M. & González-Aguilera, D. (2016a). Implementation of photogrammetry to the three-dimensional reconstruction of cut marks: an alternative to the Scanning Electron Microscopy. Poster. European Society for the Study of Human Evolution. September 2016. Alcalá de Henares (Madrid). ISSN 2195-0776 (Print) / ISSN 2195-0784 (Online).

Maté-González, M. Á., Palomeque-González, J. F., Yravedra, J., González-Aguilera, D. & Domínguez-Rodrigo, M. (2016b). Micro-photogrammetric and morphometric differentiation of cut marks on bones using metal knives, quartzite and flint flakes. Archaeological and Anthropological Sciences, DOI: 10.1007/s12520-016-0401-5.

Maté-González, M. Á., Aramendi, J., Yravedra, J., Blasco, R., Rosell, J., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017a). Assessment of statistical agreement of three techniques for the study of cut marks: 3D Digital Microscope, Laser Scanning Confocal Microscopy and Micro-Photogrammetry. Journal of Microscopy 0, 1–15. DOI: 10.1111/jmi.12575.

Maté-González, M. Á., Yravedra, J., Martín-Perea, D. M., Palomeque-González, J. F., San Juan-Blázquez, M., Estaca-Gómez, V., Uribelarrea, D., Álvarez-Alonso, D., Cuartero, F., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017b - Aceptado). Flint and quartzite: Distinguishing raw material through bone cut marks. Archaeometry.

McPherron, S. P., Alemseged, Z., Marean, C., Wynn, J. G., Reed, D., Geraads, D., Bobe, R. & Bearat, H. (2011). Tool-marked bones from before the Oldowan change the paradigm. Proc. Natl. Acad. Sci. 108, 116-116.

Moya-Maleno, P. R., Valdelomar, J. T., Madrid, D. V. & Sánchez, R. L. (2015). Interoperability of photogrammetry in 3D modeling: documentation, research and dissemination in the archaeological site of Jamila. Virtual Archaeology Review, 6(13), 51-64. http://polipapers.upv.es/index.php/var/article/view/4377/4503.

Nilsen, P. J. (2001). An actualistic butchery study in south africa and its implications for reconstructing hominid strategies of carcass acquisition and butchery in the upper Pleistocene and Plio-Pleistocene. PHD. Ph. D. Dissertation, University of Cape Town.

Ollé Cañellas, A. (2012) Microscòpia d'alta resolució aplicada a anàlisis traceològiques, tafonòmiques i zooarqueològiques. Memòria justificativa de recerca per a les convocatòries ACOM, AJOVE, ARAFI, ARIE, FJOVE, ISPC, PBR, RICIP. AGAUR.

Olsen, S. L. (1988). The identification of stone and metal tool marks on bone artefact BAR 452, 337-360.

Olsen, S. L. & Shipman, P. (1988) Surface modification on bone: Trampling Vs butchery. Journal of Archaeological Science 15, 535-553.

Palomeque-González, J. F., Maté-González, M. Á., Yravedra, J., San Juan-Blázquez, M., García Vargas, E., Martín-Perea, D. M., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017). Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones. Journal of Archaeological Science: Reports 13, 60-66. DOI: 10.1016/j.jasrep.2017.03.033.

Peale, J. (1870). On the uses of the Brain and Marrow of Animals Among the Indians of North America. Smithsonian Institution Annual Report for, 1870. 390-391.

Pickering, T., Domínguez-Rodrigo, M., Egeland, C. P. & Brain, C. K. (2004) New data and ideas on the foraging behavior of Early Stone Age hominids at Swartkrans Cave, South Africa South African Journal of Science 100, 215-218.

Pickering, T. R. & Egeland, C. P. (2006). Experimental pattern of hammerstone percussion damage on bones: implications for inferences of carcass processing by humans. Journal of Archaeological Science, 33, 459–69.

Pierdicca, R., Malinverni, E. S., Frontoni, E., Colosi, F. & Orazi, R. (2016). 3D visualization tools to explore ancient architectures in South America. Virtual Archaeology Review, 7(15), 44-53.

Pobiner, B. L., Rogersb, M. J., Monahan, C.M. & Harrisd J. W. K. (2009). New evidence for hominine carcass processing strategies at 1.5 Ma, Koobi Fora, Kenya. Journal of Human Evolution 55, 103-130.

Potts, R. & Shipman, P. (1981). Cutmarks made by stone tools on bones from Olduvai Gorge, Tanzania. Nature 291, 577-580.

Ramos, A. S., Arenas, J. M. J. & Guerrero, J. A. E. (2017). Evolución humana y antropología virtual: una propuesta para la docencia y la investigación. Revista Otarq: Otras arqueologías, (1), 267-283.

Sabina, J. Á. R., Valle, D. G., Ruiz, C. P., García, J. M. M. & Laguna, A. G. (2015). Aerial Photogrammetry by drone in archaeological sites with large structures. Methodological approach and practical application in the medieval castles of Campo de Montiel. Virtual Archaeology Review, 6(13), 5-19. http://polipapers.upv.es/index.php/var/article/view/4366/4494.

Sahnouni, M., Rosell, J., Van der Made, J., Vergès, J. M., Ollé, A., Kandi, N., Harichane, Z., Derradji, A. & Medig, M. (2012). The first evidence of cut marks and usewear traces from the Plio-Pleistocene locality of El-Kherba (Ain Hanech), Algeria: Implications for early hominin subsistence activities circa 1.8 Ma. Journal of Human Evolution 64, 137-150.

Saladié, P., Huguet, R., Díez, C., Rosell, J., Cáceres, I., Rodríguez-Hidalgo, A., Vallverdú, J., Bermúdez de Castro, J. M. & Carbonell, E. (2011). Carcass transport decisions in Homo antecessor subsistence strategies. Journal of Human Evolution 61, 425-446.

Santonja, M., Panera, J., Rubio-Jara, J., Pérez-González, A., Uribelarrea, 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.

Selvaggio, M. M. & Wilder, J. (2001). Identifying the involvement of multiple carnivore taxon with archaeological bone assemblages. J. Archaeol. Sci. 28, 465–470.

Semaw, S., Rogers, M. J., Quade, J., Renee, P. R., Butler, R. F., Stout, D., Domínguez-Rodrigo, M., Hart, W., Pickering, T. & Simpson, S. W. (2003). 2.6-Million-year-old stone tools and associated bones from OGS-6 and OGS-7, Gona, Afar, Ethiopia. Journal of Human Evolution 45, 169-177.

Shipman, P. (1981). Life History of a Fossil. An introduction to taphonomy and paleoecology. Harvard University Press.

Shipman, P. (1983). Early hominid lifestyle: hunting and gathering or foraging and scavenging. Animals and archaeology, 1, 31-49.

Shipman, P. & Rose, J. (1983). Early hominid hunting, buchering and carcass-procesing behaviours: a roaches to tha fosil record. Journal of anthropological Archaeology 2, 57-98.

Shipman, P. & Rose, J. (1984). Cutmarks mimics on modern and fossil bovid bones Current Anthropology 25 (1), 116-117.

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.

Spanò, A., Chiabrando, F., Dezzani, L. & Prencipe, A. (2016). Digital Segusio: from models generation to urban reconstruction. Virtual Archaeology Review, 7(15), 87-97. http://polipapers.upv.es/index.php/var/article/view/5874/6833.

Spennerman, D. H. R. (1990). Don't forget the bamboo on recognising and interpretating butchery narcks in tropical faunal assemblages some comments asking for cauting. Solomon S. Davidson I. Watson D. (eds) Problems Solving Taphonomy Tempus 2, 80-101.

Stringer, C., Finlayson, C., Barton, R. N. E, Fernández-Jalvo, Y. & Cáceres, I. (2008). Neanderthal exploitation of marine mammals in Gibraltar. Proc. Natl. Acad. Sci. 10538, 14319-14324.

Tabachnick, B. G. & Fidell, L. S. (2012). Using multivariate statistics (6th ed.). Boston, MA: Pearson.

Thompson, J. C., McPherron, S. P., Bobe, R. E., Reed, D. E., Barr, W. A., Wynn, J., Marean, C. V., Geraads, D. & Alemseged, Z. (2015). Taphonomy of fossils from the hominin-bearing deposits at Dikika, Ethiopia. Journal of human Evolution 86, 112-135.

Torres-Martínez, J. A., Seddaiu, M., Rodríguez-Gonzálvez, P., Hernández-López, D. & González-Aguilera, D. (2016). A Multi-Data Source and Multi-Sensor Approach for the 3D Reconstruction and Web Visualization of a Complex Archaelogical Site: The Case Study of "Tolmo De Minateda". Remote Sensing, 8(7), 550.

Vera, J. A. B., Romero, A. P., Marín, R. O. & Gutiérrez, C. C. (2011). Nuevas tecnologías en levantamientos aplicadas a la restauración: "El Giraldillo''. Virtual Archaeology Review, 2(3), 115-120.

Walker, P. L. & Long, J. C. (1977). An experimental study of the morphological characteristics of cut marks. American Antiquity 42, 605–616.

Walker, P. L. (1978). Butchering and stone tool function. American Antiquity 43, 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.

White, T. E. (1952). Observations on the butchering technique of some aboriginal peoples, 1. American Antiquity, 17, 337-338.

White, T. E. (1953). Observations on the butchering technique of some aboriginal peoples, 2. American Antiquity, 19, 160-164.

White, T. E. (1954). Observations on the butchering technique of some aboriginal peoples, 3, 4, 5, 6. American Antiquity, 19, 254-264.

White, T. E. (1955). Observations on the butchering technique of some aboriginal peoples, 7, 8, 9. American Antiquity, 21, 170-178.

White, T. E. (1992). Prehistoric Cannibalism at Mancos 5MTUMR-2346. Princeton University Press, Princeton.

Yravedra, J., Morín, J., Agustí, E., Sanabria, P., López, M., Urbina, D., López-Frailes, F. J., López, G. & Illán, J. (2009). Implicaciones Metalúrgicas de las marcas de corte en la transición Bronce Final-Hierro en el interior de la Península Ibérica.

Yravedra, J., Domínguez-Rodrigo, M., Santonja, M., Pérez-González, A., 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, 2469-2476.

Yravedra, J., Lagos, L. & Bárcena, F. (2011). A Taphonomic Study of Wild Wolf (Canis lupus) Modification of Horse Bones in Northwestern Spain. Journal of Taphonomy. 9(1), 37-65.

Yravedra, J., Rubio-Jara, S., Panera, J., Uribelarrea, D. & Pérez-González, A. (2012). Elephants and subsistence. Evidence of the human exploitation of extremely large mammal bones from the Middle Palaeolithic site of PRERESA (Madrid, Spain Journal of Archaeological Science 39, 1063-1071.

Yravedra, J., Maté-González, M. Á., Palomeque-González, J. F., Aramendi, J., Estaca-Gómez, V., San Juan Blazquez, M., García Vargas, E., Organista, E., González-Aguilera, D., Arriaza, M. C., Cobo-Sánchez, L., Gidna, A., Uribelarrea del Val, U., Baquedano, E., Mabulla, A. & Domínguez-Rodrigo, M. (2017a). 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. Boreas, DOI: 10.1111/bor.12224.

Yravedra, J., Diez-Martin, F., Egeland, C. P., Maté-González, M. Á., Palomeque-González, J. F., Arriaza, M. C., Aramendi, J., García Vargas, E., Estaca-Gómez, V., Sanchez, P., Fraile, C., Duque, J., de Francisco Rodriguez, S., González-Aguilera, D., Uribelarrea, D., Mabulla, A., Baquedano, E. & Dominguez-Rodrigo, M. (2017b). FLK West (Lower Bed II, Olduvai-Gorge, Tanzania): A new early Acheulean site with evidence for human exploitation of fauna. Boreas.

Zambanini, S., Schlapke, M., Kampel, M. & Müller, A. (2009). Historical coins in 3D: acquisition and numismatic applications. In Proceedings of the International Symposium on Virtual Reality, Archaeology and Cultural Heritage (VAST) (pp. 49-52).

Anexo I: Datos estadísticos de las revistas

Índices de calidad de las revistas científicas.

Los datos que aparecen en le siguiete anexo están disponibles en SCImago Journal & Country Rank (http://www.scimagojr.com). Scientific journal quality indexes. Understanding indicators, tables and charts.

SJR (SCImago Journal Rank) indicator. It expresses the average number of weighted citations received in the selected year by the documents published in the selected journal in the three previous years.

H Index. The h index expresses the journal's number of articles (h) that have received at least h citations. It quantifies both journal scientific productivity and scientific impact and it is also applicable to scientists, countries, etc.

Total Documents. Output of the selected period. All types of documents are considered, including citable and non-citable documents.

Total Documents (3years). Published documents in the three previous years (selected year documents are excluded). All types of documents are considered, including citable and non-citable documents.

Citable Documents (3 years). Number of citable documents published by a journal in the three previous years (selected year documents are excluded). Exclusively articles, reviews and conference papers are considered.

Total Cites (3years). Number of citations received in the seleted year by a journal to the documents published in the three previous years. All types of documents are considered.

Non-citable Docs. (Available in the graphics). Non-citable documents ratio in the period being considered.

Self Cites. Number of journal's self-citations in the seleted year to its own documents published in the three previous years. All types of documents are considered.

Cites per Document (2 years). Average citations per document in a 2 year period. It is computed considering the number of citations received by a journal in the current year to the documents published in the two previous years.

Cites per Document (3 years). Average citations per document in a 3 year period. It is computed considering the number of citations received by a journal in the current year to the documents published in the three previous years.

Cites per Document (4 years). Average citations per document in a 4 year period. It is computed considering the number of citations received by a journal in the current year to the documents published in the four previous years.

Cited Documents. Number of documents cited at least once in the three previous years.

Uncited Documents. Number of uncited documents in the three previous years.

Total References. It includes all the bibliographical references in a journal in the selected period.

References per Document. Average number of references per document in the selected year.

% International Collaboration. Document ratio whose affiliation includes more than one country address.

Journal of Archaeological Science

- Publisher: Academic Press Inc.
- Country: United States
- ISSN: 0305-4403 E-ISSN: 1095-9238
- URL: https://www.journals.elsevier.com/journal-of-archaeological-science/
- Impact Factor (2015): 2.255
- 5-Year Impact Factor: 2.406
- Source Normalized Impact per Paper (SNIP-2015): 1.318
- SCImago Journal Rank (SJR-2015): 1.583
- H Index: 82
- CiteScore (SCOPUS-2015): 2.59
- Quartile (Journal Citation Reports - 2015):

  Rank:

  10/84 (Q1) Anthropology

  28/2131 (Q1) Social sciences, general

  58/184 (Q2) Geosciences, multidisciplinary
- Quartile (SCImago Journal Rank - 2015):

  Rank:

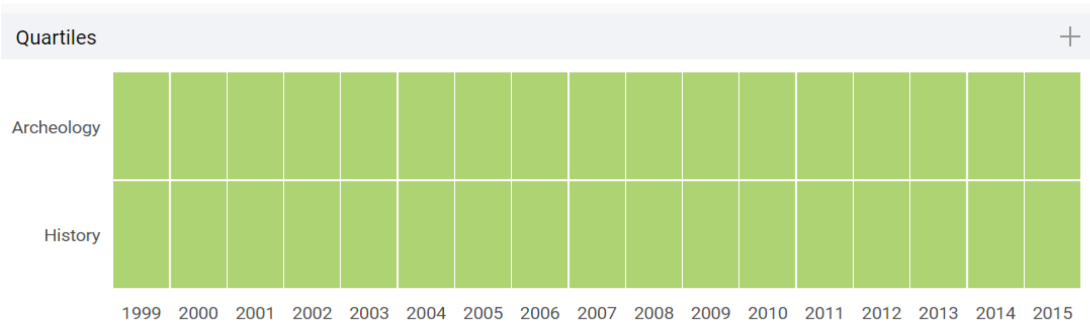
  (Q1) History

  (Q1) Archeology
- Quartile (SCOPUS-2015):

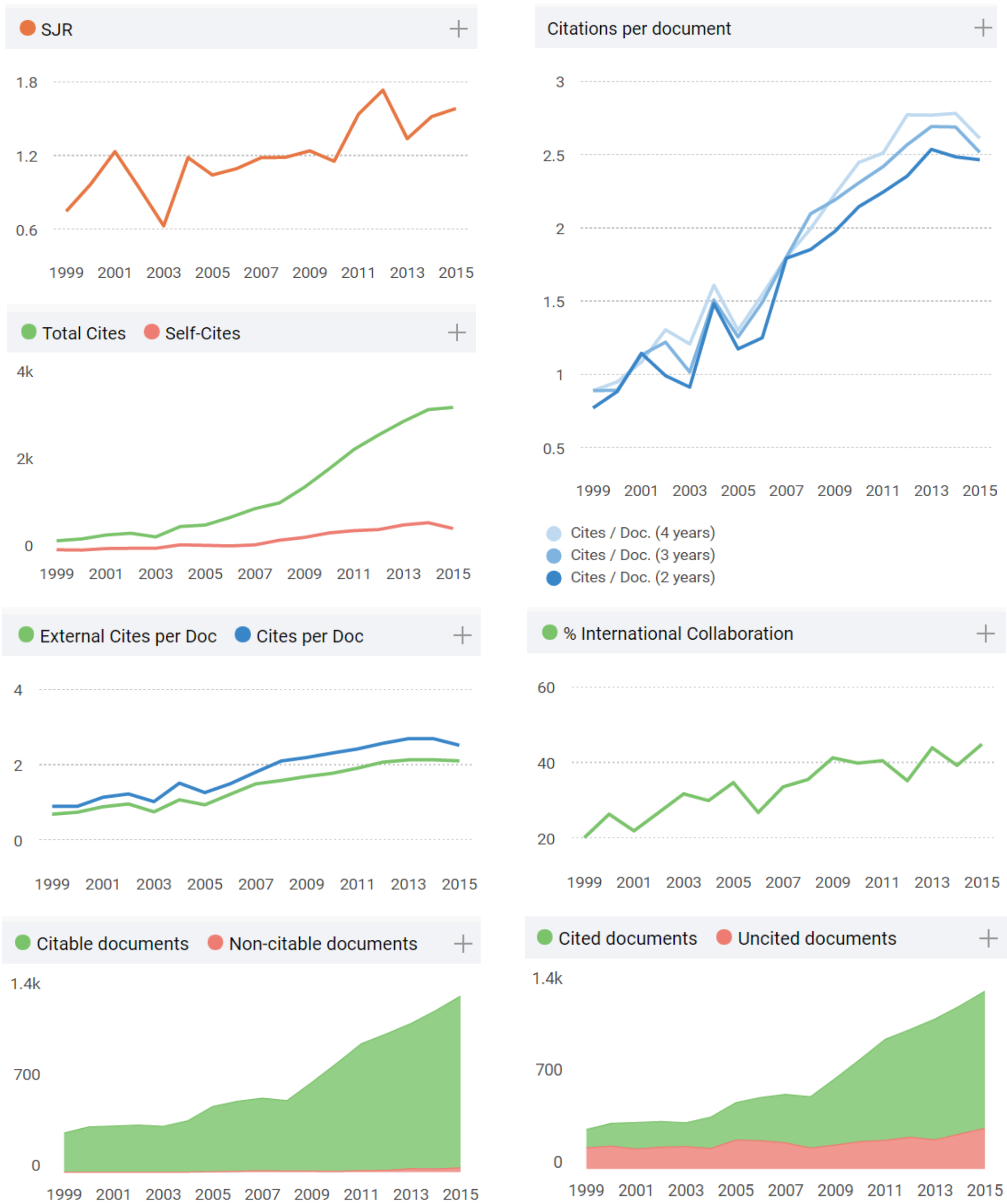
  Rank:

  3/858 (Q1) History

  5/204 (Q1) Archeology



Q1 (green), Q2 (yellow), Q3 (orange), Q4 (red).



Scimago Journal & Country Rank (http://www.scimagojr.com).

Note: “k” is expressed in thousands of documents or citations.

Archaeological and Anthropological Sciences

- Publisher: Springer Berlin Heidelberg
- Country: Germany
- ISSN: 1866-9557 ISSN: 1866-9565
- URL: https://link.springer.com/journal/12520
- Impact Factor (2015): 1.636
- 5-Year Impact Factor: 1.752
- Source Normalized Impact per Paper (SNIP-2015): 0.866
- SCImago Journal Rank (SJR-2015): 1.056
- H Index: 15
- CiteScore (SCOPUS-2015): 1.62
- Quartile (Journal Citation Reports - 2015):

  Rank:

  21/84 (Q1) Anthropology

  1406/2131 (Q3) Social sciences, general

  95/184 (Q3) Geosciences, multidisciplinary
- Quartile (SCImago Journal Rank - 2015):

  Rank:

  (Q1) Anthropology

  (Q1) Archeology

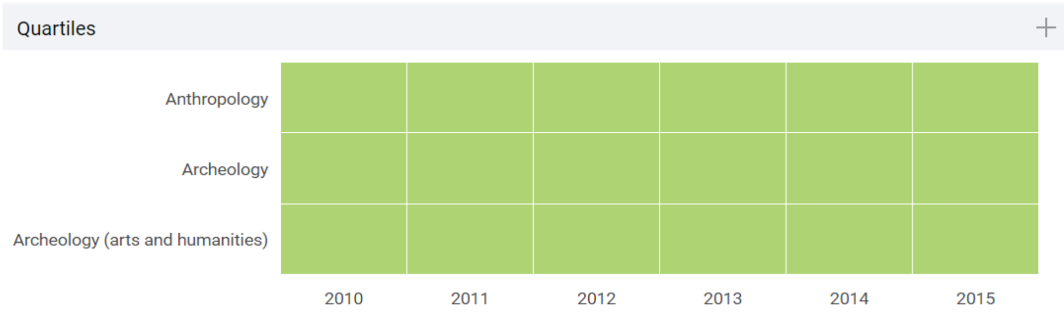
  (Q1) Archeology (arts and humanities)
- Quartile (SCOPUS-2015):

  Rank:

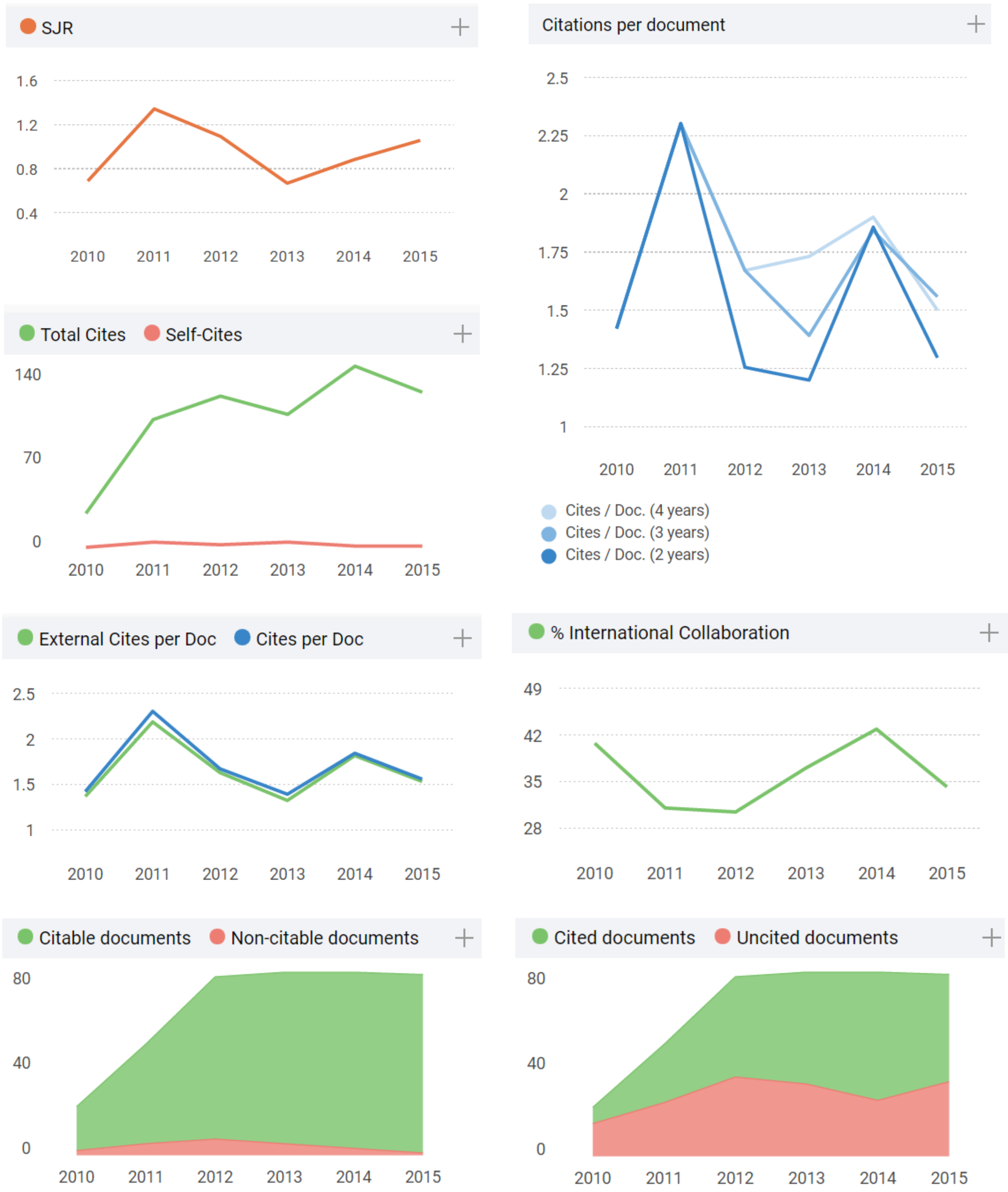
  25/273 (Q1) Anthropology

  11/204 (Q1) Archeology

  12/205 (Q1) Archeology (arts and humanities)



Q1 (green), Q2 (yellow), Q3 (orange), Q4 (red).



Scimago Journal & Country Rank (http://www.scimagojr.com).

Note: “k” is expressed in thousands of documents or citations.

Boreas

- Publisher: Wiley-Blackwell
- Country: United Kingdom
- ISSN: 0300-9483 E-ISSN: 1502-3885
- URL: http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1502-3885
- Impact Factor (2015): 2.386
- 5-Year Impact Factor: 2.709
- Source Normalized Impact per Paper (SNIP-2015): 1.095
- SCImago Journal Rank (SJR-2015): 1.553
- H Index: 56
- CiteScore (SCOPUS-2015): 2.79
- Quartile (Journal Citation Reports - 2015):

  Rank:

  149/408 (Q2) Geosciences

  18/49 (Q2) Geography, physical

  49/184 (Q2) Geosciences, multidisciplinary
- Quartile (SCImago Journal Rank - 2015):

  Rank:

  (Q1) Archaeology (arts and humanities)

  (Q1) Ecology, Evolution, Behavior and Systematics

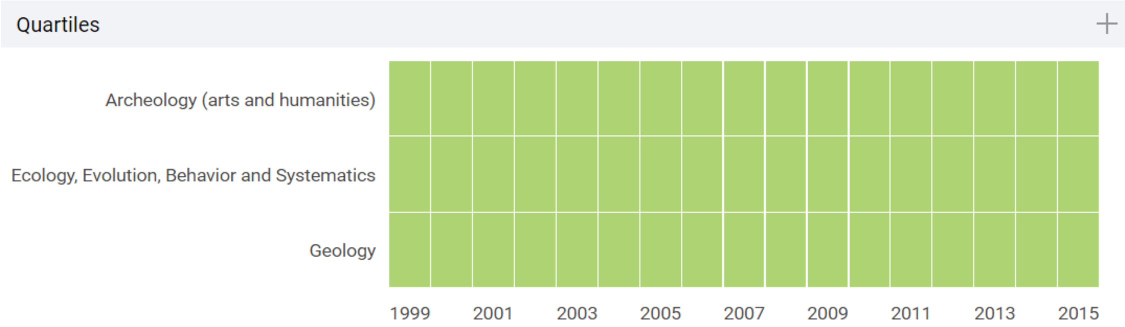
  (Q1) Geology
- Quartile (SCOPUS-2015):

  Rank:

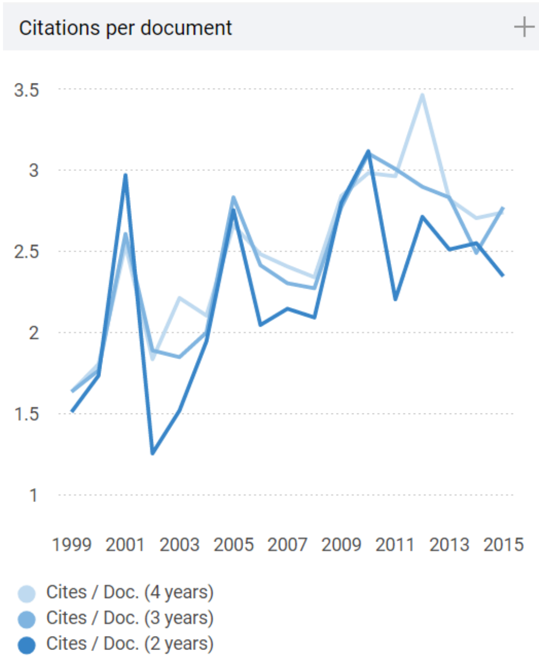
  4/205 (Q1) Archaeology (arts and humanities)

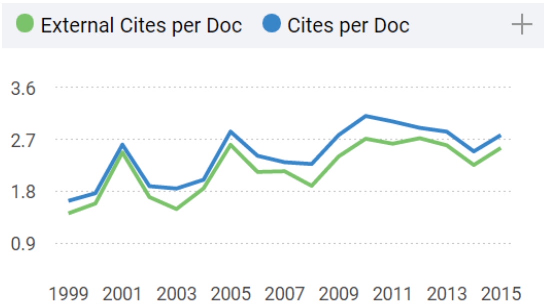
  72/517 (Q1) Ecology, Evolution, Behavior and Systematics

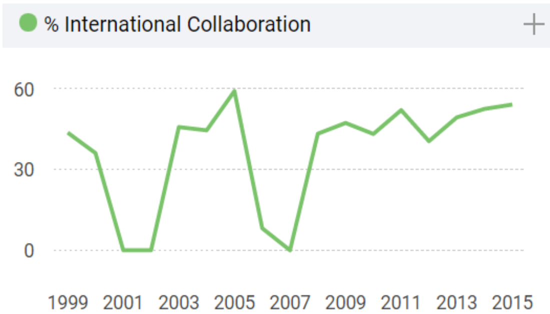
  21/201 (Q1) Geology

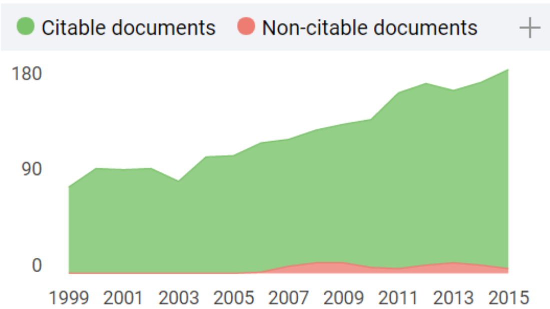


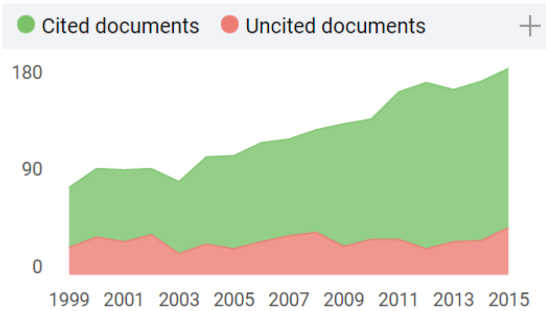
Q1 (green), Q2 (yellow), Q3 (orange), Q4 (red).











Scimago Journal & Country Rank (http://www.scimagojr.com).

Note: “k” is expressed in thousands of documents or citations.

Palaeogeography, Palaeoclimatology, Palaeoecology

- Publisher: Elsevier
- Country: Netherlands
- ISSN: 0031-0182
- URL: https://www.journals.elsevier.com/palaeogeography-palaeoclimatology-palaeoecology
- Impact Factor (2015): 2.525
- 5-Year Impact Factor: 3.020
- Source Normalized Impact per Paper (SNIP-2015): 1.069
- SCImago Journal Rank (SJR-2015): 1.501
- H Index: 112
- CiteScore (SCOPUS-2015): 2.67
- Quartile (Journal Citation Reports - 2015):

  Rank:

  16/49 (Q2) Geography, physical

  44/184 (Q1) Geosciences, multidisciplinary

  4/54 (Q1) Paleontology
- Quartile (SCImago Journal Rank - 2015):

  Rank:

  (Q1) Earth-Surface Processes

  (Q1) Ecology, Evolution, Behavior and Systematics

  (Q1) Oceanography

  (Q1) Paleontology
- Quartile (SCOPUS-2015):

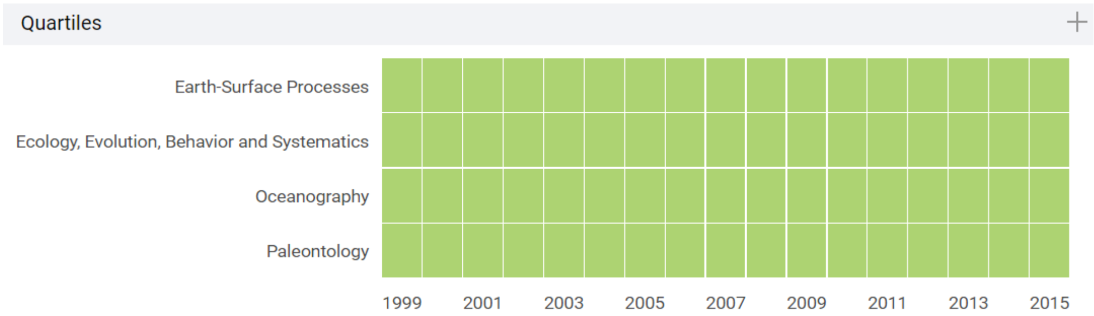
  Rank:

  8/88 (Q1) Paleontology

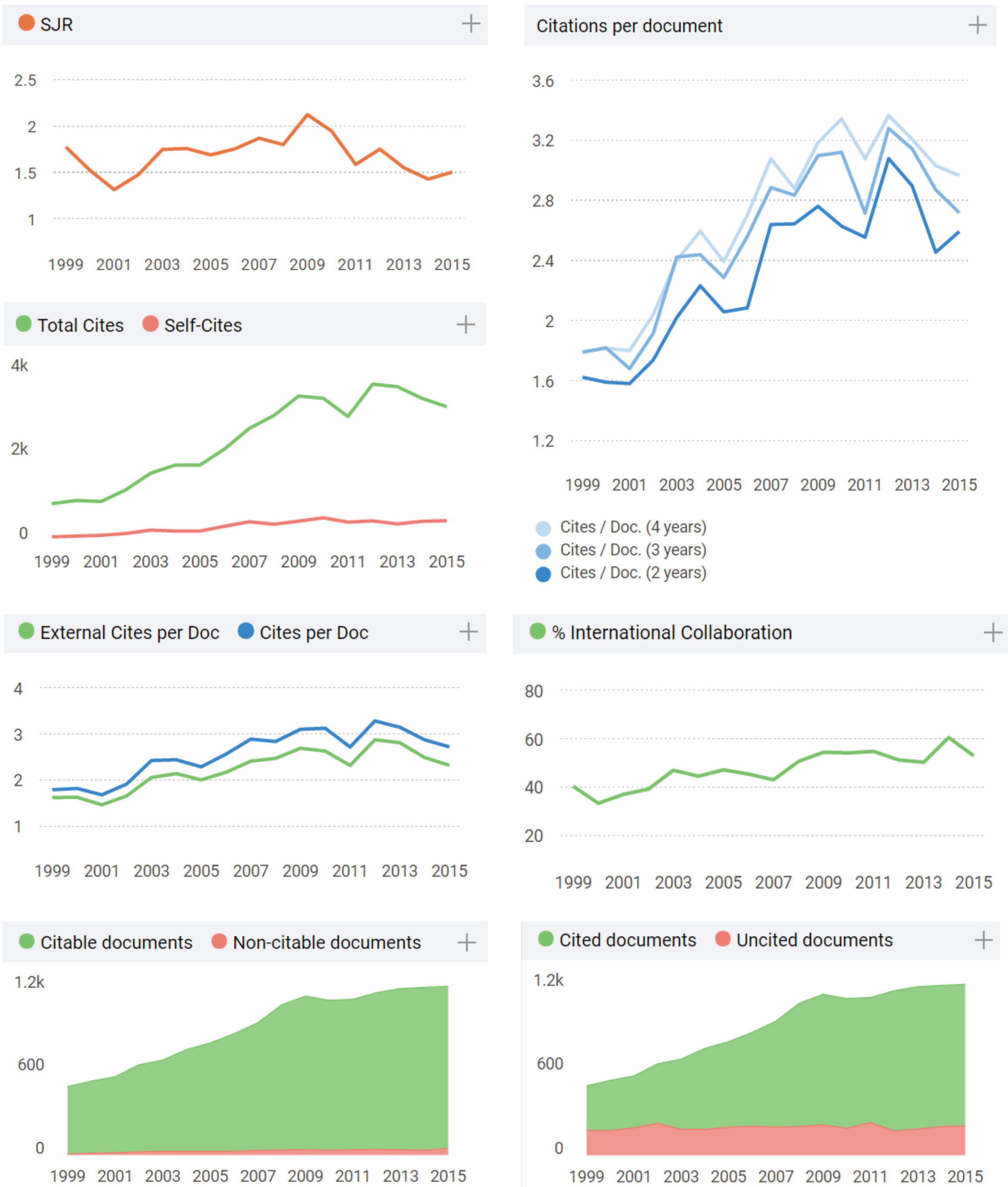
  17/125 (Q1) Earth-Surface Processes

  16/110 (Q1) Oceanography

  76/517 (Q1) Ecology, Evolution, Behavior and Systematics



Q1 (green), Q2 (yellow), Q3 (orange), Q4 (red).



Scimago Journal & Country Rank (http://www.scimagojr.com).

Note: “k” is expressed in thousands of documents or citations.

Archaeometry

- Publisher: Wiley-Blackwell
- Country: United Kingdom
- ISSN: 0003-813XE-ISSN:1475-4754
- URL: http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1475-4754
- Impact Factor (2015): 1.364
- 5-Year Impact Factor: 1.424
- Source Normalized Impact per Paper (SNIP-2015): 1.051
- SCImago Journal Rank (SJR-2015): 0.809
- H Index: 48
- CiteScore (SCOPUS-2015): 1.41
- Quartile (Journal Citation Reports - 2015):

  Rank:

  30/46 (Q3) Chemistry Inorganic & Nuclear

  51/75 (Q3) Chemistry Analytical

  115/184 (Q3) Geosciences Multidisciplinary
- Quartile (SCImago Journal Rank - 2015):

  Rank:

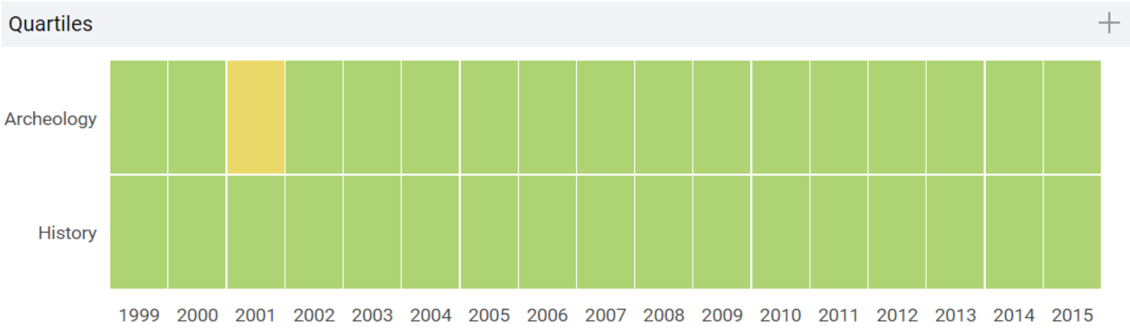
  (Q1) Archeology

  (Q1) History
- Quartile (SCOPUS-2015):

  Rank:

  22/858 (Q1) History

  16/204 (Q1) Archeology



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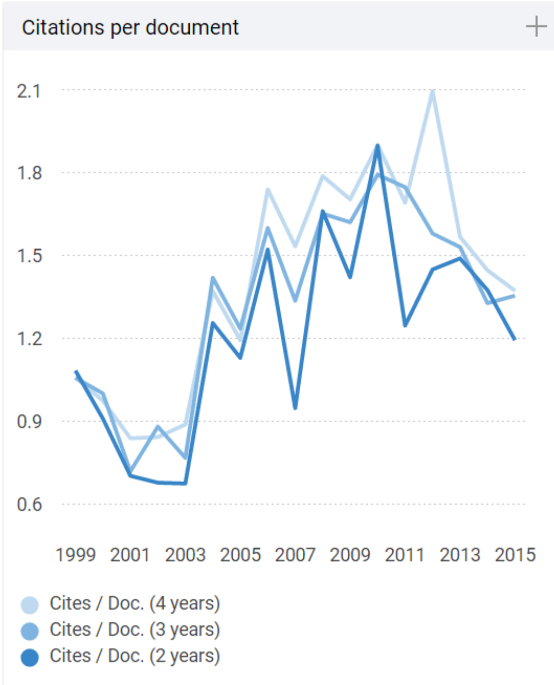
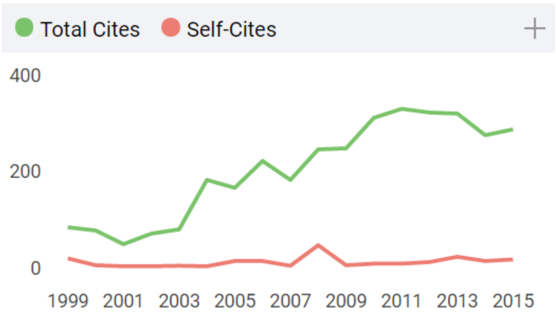
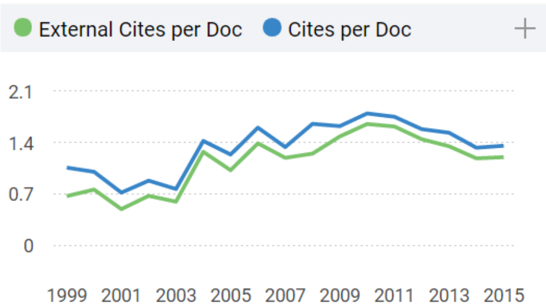
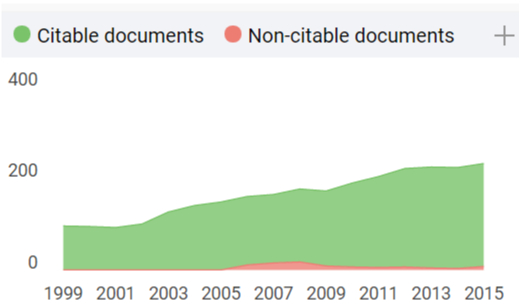
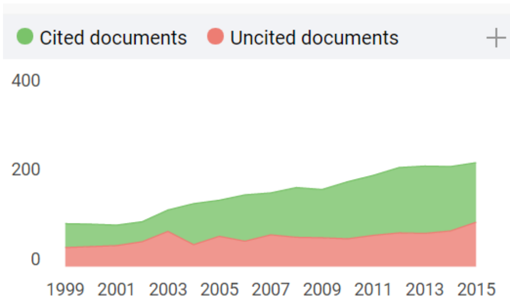










Scimago Journal & Country Rank (http://www.scimagojr.com).

Note: “k” is expressed in thousands of documents or citations.

Journal of Microscopy

- Publisher: Blackwell Publishing Inc.
- Country: United Kingdom
- ISSN: 0022-2720 E-ISSN: 1365-2818
- URL: http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1365-2818
- Impact Factor (2015): 2.136
- 5-Year Impact Factor: 2.034
- Source Normalized Impact per Paper (SNIP-2015): 1.091
- SCImago Journal Rank (SJR-2015): 1.017
- H Index: 88
- CiteScore (SCOPUS-2015): 2.37
- Quartile (Journal Citation Reports - 2015):

  Rank:

  3/10 (Q2) Microscopy
- Quartile (SCImago Journal Rank - 2015):

  Rank:

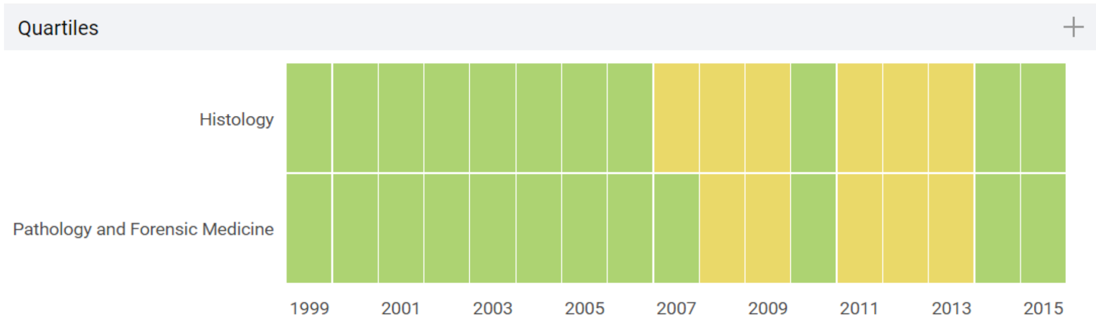
  (Q1) Histology

  (Q1) Pathology and Forensic Medicine
- Quartile (SCOPUS-2015):

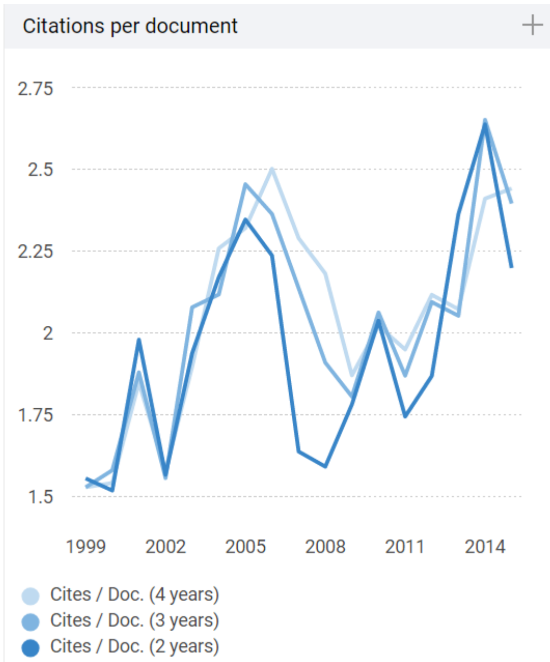
  Rank:

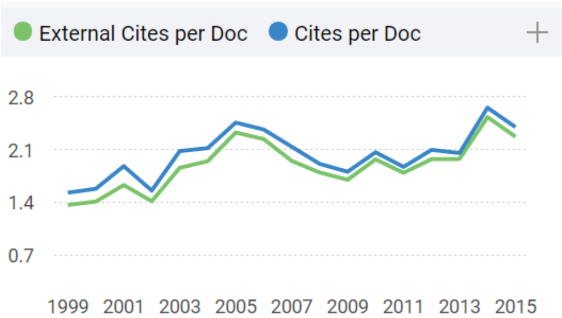
  9/55 (Q1) Histology

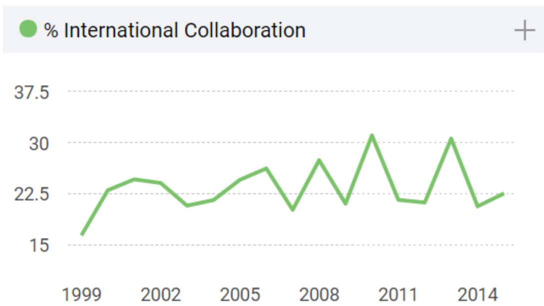
  33/187 (Q1) Pathology and Forensic Medicine

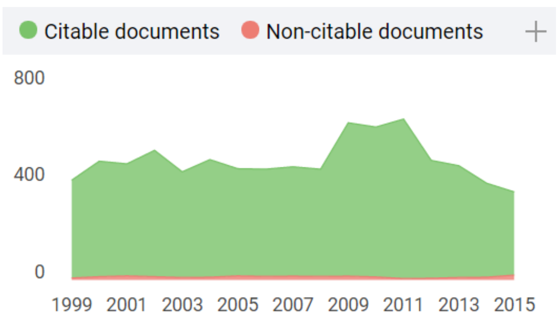


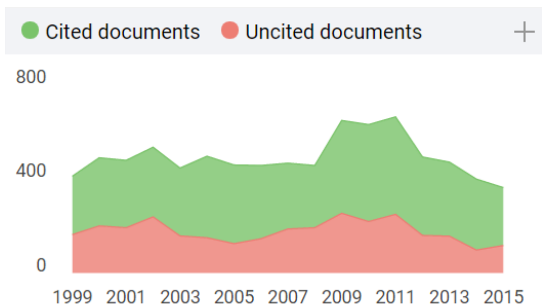
Q1 (green), Q2 (yellow), Q3 (orange), Q4 (red).











Scimago Journal & Country Rank (http://www.scimagojr.com).

Note: “k” is expressed in thousands of documents or citations.

Anexo II: Otras publicaciones

Congresos internacionales

- Título: **Implementation of photogrammetry to the three-dimensional reconstruction of cut marks: an alternative to the Scanning Electron Microscopy.**

Año de publicación: 2016
Congreso: Poster. European Society for the Study of Human Evolution. September 2016. Alcalá de Henares (Madrid). ISSN 2195-0776 (Print) / ISSN 2195-0784 (Online).
Autores: **Maté-González, M. Á.**, Palomeque-González, J. F., Yravedra, J., Domínguez-Rodrigo, M. & González-Aguilera, D.

Resumen:

Durante los últimos años la tafonomía ha demostrado ser una disciplina de gran importancia para la explicación de los yacimientos arqueológicos. Entre los diferentes procesos tafonómicos que pueden ir asociados a la acción humana, las marcas de corte han suscitado un gran interés en la explicación del comportamiento alimenticio humano. Su representación, frecuencia, distribución y significado han sido ampliamente utilizados para la interpretación de los yacimientos paleolíticos. Llegados a este punto, se impone como crucial la correcta definición de dichas marcas, así como la información que se puede obtener de ellas, como por ejemplo la identificación de las materias primas utilizadas en el procesado de un animal. Por ello, diversos investigadores han experimentado con diferentes métodos para poder estudiar mejor las marcas de corte. El método más conocido es el relacionado con la microscopía electrónica de barrido (SEM), que durante los últimos años ha alcanzado resultados espectaculares.

Los principales problemas que presenta la aplicación de estas técnicas son:

- El elevado coste económico.
- La gran cantidad de tiempo que se emplea en su aplicación.
- La preparación previa necesaria de las muestras antes de someterse a estos estudios.
- La necesidad de un equipo técnico especializado para manejar estos equipos.

Para solucionar estos problemas, y poder aumentar el volumen de datos susceptibles de ser analizados, en este trabajo planteamos el uso de técnicas micro-fotogramétricas combinadas con la visión computacional, la morfométrica geométrica y la estadística para poder realizar estos estudios. Finalmente, plantearemos nuevas vías de investigación a las que éste procedimiento es fácilmente aplicable.

6th Annual Meeting of the

European Society for the study of Human Evolution

14-17 September 2016
MADRID / SPAIN

ESHE

European Society for the study of Human Evolution

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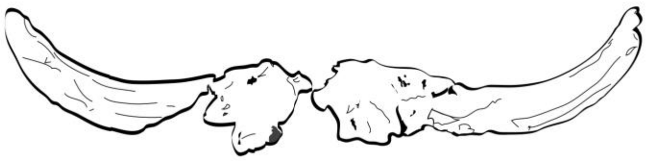
6th Annual Meeting

Madrid, Spain 14 -17 September, 2016



Cover image: Bison Horns courtesy of the Museo Arqueológico Regional

Proceedings of the European Society for the study of Human Evolution Vol. 5

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ISSN 2195-0776 (Print)

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Poster Presentation Number 60, We (17:00-19:00)

Implementation of photogrammetry to the three-dimensional reconstruction of cut marks: an alternative to the Scanning Electron Microscopy

Miguel Ángel Maté-González[1,2], Juan Francisco Palomeque-González[3], José Yravedra[3], Manuel Domínguez-Rodrigo[3,4], Diego González-Aguilera[1]

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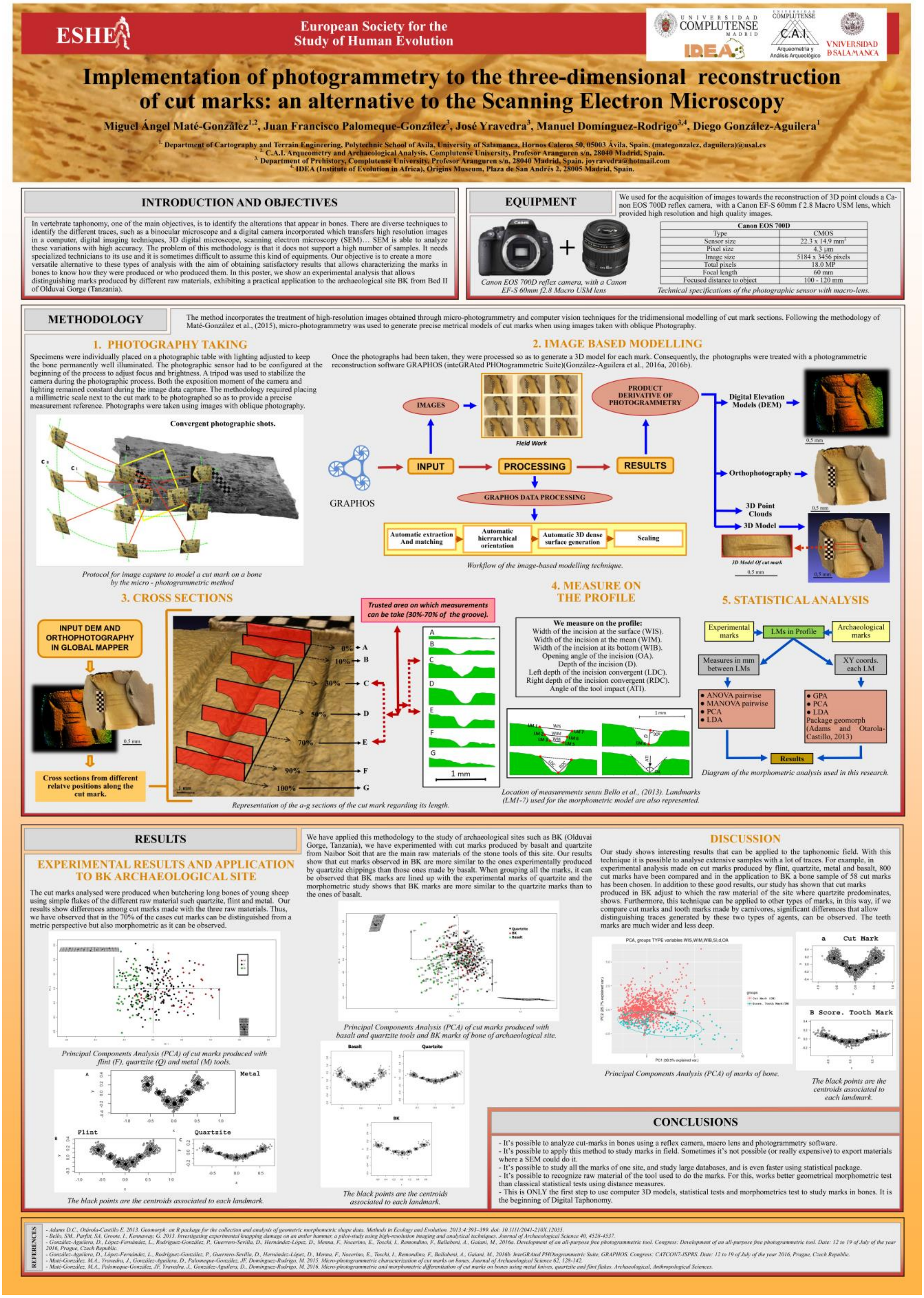
During the last decades taphonomy has proven to be a discipline of great importance for the explanation of archaeological and palaeontology sites. Among the different taphonomic processes that can be associated to human actions, cut marks have been of great interest to explain human nutritional behaviour and it is a key tool in the explanation of hunting-scavenging debate. The presence, the frequency, the distribution, and the meaning of cut marks of bones have been thoroughly used to interpret Palaeolithic and archaeological sites. Thus, at this point, the right definition of these marks, the information obtained from them, as well as the identification of raw materials used in animal processing is crucial. Therefore, various researchers have experimented with different methods to better observe cut marks. The best method known to date is the one based on Scanning Electron Microscopy (SEM), by which during the last years researchers have been able to achieve spectacular results generating three-dimensional models of cut marks of bones.

The main problem that these techniques pose is their high cost in money and time that is necessary to gather the necessary equipment, and to carry out the preparation that marks must experiment before being processed. In order to solve this problem and with the aim of increasing the volume of data susceptible to be analysed, in this work we outline the use of photogrammetry by macro lens to carry out these studies, we describe the previous process of investigation in detail, as well as the technique used, and we show the results that arise from their use. Statistical and morphometric studies were carried out on several hundreds of silhouettes of experimental cut marks made with different raw materials (flint, basalt, quartzite, and metal). This sample constitutes one of the biggest databases of this kind of data compiled up to the present day. Finally, we suggest new lines of investigation to which this procedure could be easily applicable.

References[1] Bello, S.M., De Groote, I., Delbarre, G., (2013a). Application of 3-dimensional microscopy and micro-CT scanning to the analysis of Magdalenian portable art on bone and antler. J. Archaeol. Sci. 40, 2464e2476. [2] 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. [3] Greenfield HJ (2006b). Slicing cut marks on animal bones: diagnostics for identifying stone tool type and raw material. Journal of Field Archaeology 31: 147-163. [4] Maté-González MA, 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. [5] Olsen SL (1988). The identification of stone and metal tool marks on bone artefact BAR 452: 337-360.


ESHE
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C.A.I. Arqueometría y Análisis Arqueológico
VNIVERSIDAD DSALAMANCA
Implementation of photogrammetry to the three-dimensional reconstruction of cut marks: an alternative to the Scanning Electron Microscopy
Miguel Ángel Maté-González[1,2], Juan Francisco Palomeque-González[3], José Yravedra[3], Manuel Domínguez-Rodrigo[3,4], Diego González-Aguilera[1]
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[2] C.A.I. Arqueometry and Archaeological Analysis, Complutense University, Profesor Aranguren s/n, 28040 Madrid, Spain.
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INTRODUCTION AND OBJECTIVES
In vertebrate taphonomy, one of the main objectives, is to identify the alterations that appear in bones. There are diverse techniques to identify the different traces, such as a binocular microscope and a digital camera incorporated which transfers high resolution images in a computer, digital imaging techniques, 3D digital microscope, scanning electron microscopy (SEM)… SEM is able to analyze these variations with high accuracy. The problem of this methodology is that it does not support a high number of samples. It needs specialized technicians to its use and it is sometimes difficult to assume this kind of equipments. Our objective is to create a more versatile alternative to these types of analysis with the aim of obtaining satisfactory results that allows characterizing the marks in bones to know how they were produced or who produced them. In this poster, we show an experimental analysis that allows distinguishing marks produced by different raw materials, exhibiting a practical application to the archaeological site BK from Bed II of Olduvai Gorge (Tanzania).
EQUIPMENT
We used for the acquisition of images towards the reconstruction of 3D point clouds a Canon EOS 700D reflex camera, with a Canon EF-S 60mm f 2.8 Macro USM lens, which provided high resolution and high quality images.
Canon EOS 700D reflex camera, with a Canon EF-S 60mm f2.8 Macro USM lens
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
Technical specifications of the photographic sensor with macro-lens.
METHODOLOGY
The method incorporates the treatment of high-resolution images obtained through micro-photogrammetry and computer vision techniques for the tridimensional 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.
1. PHOTOGRAPHY TAKING
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 taken using images with oblique photography.
Convergent photographic shots.
Protocol for image capture to model a cut mark on a bone by the micro - photogrammetric method
2. IMAGE BASED MODELLING
Once the photographs had been taken, they were processed so as to generate a 3D model for each mark. Consequently, the photographs were treated with a photogrammetric reconstruction software GRAPHOS (inteGRAted PHOtogrammetric Suite)(González-Aguilera et al., 2016a, 2016b).
IMAGES
Field Work
PRODUCT DERIVATIVE OF PHOTOGRAMMETRY
GRAPHOS
INPUT
PROCESSING
RESULTS
GRAPHOS DATA PROCESSING
Automatic extraction And matching
Automatic hierrarchical orientation
Automatic 3D dense surface generation
Scaling
Workflow of the image-based modelling technique.
Digital Elevation Models (DEM)
Orthophotography
3D Point Clouds
3D Model
3D Model Of cut mark
0.5 mm
3. CROSS SECTIONS
INPUT DEM AND ORTHOPHOTOGRAPHY IN GLOBAL MAPPER
Cross sections from different relatve positions along the cut mark.
Trusted area on which measurements can be take (30%-70% of the groove).
0% A
10% B
30% C
50% D
70% E
90% F
100% G
1 mm
Representation of the a-g sections of the cut mark regarding its length.
4. MEASURE ON THE PROFILE
We measure on the profile:
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 of the incision (OA).
Depth of the incision (D).
Left depth of the incision convergent (LDC).
Right depth of the incision convergent (RDC).
Angle of the tool impact (ATI).
Location of measurements sensu Bello et al., (2013). Landmarks (LM1-7) used for the morphometric model are also represented.
5. STATISTICAL ANALYSIS
Experimental marks
LMs in Profile
Archaeological marks
Measures in mm between LMs
XY coords. each LM
• ANOVA pairwise
• MANOVA pairwise
• PCA
• LDA
• GPA
• PCA
• LDA
Package geomorph (Adams and Otarola-Castillo, 2013)
Results
Diagram of the morphometric analysis used in this research.
RESULTS
EXPERIMENTAL RESULTS AND APPLICATION TO BK ARCHAEOLOGICAL SITE
The cut marks analysed were produced when butchering long bones of young sheep using simple flakes of the different raw material such quartzite, flint and metal. Our results show differences among cut marks made with the three raw materials. Thus, we have observed that in the 70% of the cases cut marks can be distinguished from a metric perspective but also morphometric as it can be observed.
Principal Components Analysis (PCA) of cut marks produced with flint (F), quartzite (Q) and metal (M) tools.
Metal
Flint
Quartzite
The black points are the centroids associated to each landmark.
We have applied this methodology to the study of archaeological sites such as BK (Olduvai Gorge, Tanzania), we have experimented with cut marks produced by basalt and quartzite from Naibor Soit that are the main raw materials of the stone tools of this site. Our results show that cut marks observed in BK are more similar to the ones experimentally produced by quartzite chippings than those ones made by basalt. When grouping all the marks, it can be observed that BK marks are lined up with the experimental marks of quartzite and the morphometric study shows that BK marks are more similar to the quartzite marks than to the ones of basalt.
Quartzite
BK
Basalt
Principal Components Analysis (PCA) of cut marks produced with basalt and quartzite tools and BK marks of bone of archaeological site.
Basalt
Quartzite
BK
The black points are the centroids associated to each landmark.
DISCUSSION
Our study shows interesting results that can be applied to the taphonomic field. With this technique it is possible to analyse extensive samples with a lot of traces. For example, in experimental analysis made on cut marks produced by flint, quartzite, metal and basalt, 800 cut marks have been compared and in the application to BK a bone sample of 58 cut marks has been chosen. In addition to these good results, our study has shown that cut marks produced in BK adjust to which the raw material of the site where quartzite predominates, shows. Furthermore, this technique can be applied to other types of marks, in this way, if we compare cut marks and tooth marks made by carnivores, significant differences that allow distinguishing traces generated by these two types of agents, can be observed. The teeth marks are much wider and less deep.
PCA, groups TYPE variables WIS,WIM,WIB,SI,d,OA
Principal Components Analysis (PCA) of marks of bone.
a Cut Mark
B Score. Tooth Mark
The black points are the centroids associated to each landmark.
CONCLUSIONS
- It's possible to analyze cut-marks in bones using a reflex camera, macro lens and photogrammetry software.
- It's possible to apply this method to study marks in field. Sometimes it's not possible (or really expensive) to export materials where a SEM could do it.
- It's possible to study all the marks of one site, and study large databases, and is even faster using statistical package.
- It's possible to recognize raw material of the tool used to do the marks. For this, works better geometrical morphometric test than classical statistical tests using distance measures.
- This is ONLY the first step to use computer 3D models, statistical tests and morphometrics test to study marks in bones. It is the beginning of Digital Taphonomy.
REFERENCES
- Adams D.C., Otárola-Castillo E. 2013. Geomorph: an R package for the collection and analysis of geometric morphometric shape data. Methods in Ecology and Evolution. 2013;4:393–399. doi: 10.1111/2041-210X.12035.
- Bello, SM., Parfitt, SA, Groote, I., Kennaway, G. 2013. Investigating experimental knapping damage on an antler hammer, a pilot-study using high-resolution imaging and analytical techniques. Journal of Archaeological Science 40, 4528-4537.
- 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.
- 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.

Anexo III: Repercusión de los artículos entre la comunidad científica.

A continuación se detalla el historial de los artículos que conforman las investigaciones de esta Tesis Doctoral y la repercusión de estos entre la comunidad científica internacional, hasta el 20 de mayo de 2017, fecha de redacción de esta Tesis Doctoral.

- **Micro-photogrammetric characterization of cut marks on bones.**

Maté-González, M. Á., Yravedra, J., González-Aguilera, D., Palomeque-González, J. F. & Domínguez-Rodrigo, M. (2015). Micro-photogrammetric characterization of cut marks on bones. Journal of Archaeological Science 62, 128-142. DOI: 10.1016/j.jas.2015.08.006.

Enviado: 1 junio 2015
Aceptado: 4 agosto 2015
Publicado online: 6 agosto 2015
Publicado: octubre 2015
Total de citas: 14
Autocitas: 8

Investigaciones donde se ha citado la publicación:

- **On Applications of Micro-photogrammetry and Geometric Morphometrics to Studies of Tooth Mark Morphology: the modern Olduvai Carnivore Site (Tanzania).**

Arriaza, M. C., Yravedra, J., Domínguez-Rodrigo, M., Maté-González, M. Á., García Vargas, E., Palomeque-González, J. F., Aramendi, J., González-Aguilera, D. & Baquedano, E. (2017). On Applications of Micro-photogrammetry and Geometric Morphometrics to Studies of Tooth Mark Morphology: the modern Olduvai Carnivore Site (Tanzania). Palaeogeography, Palaeoclimatology, Palaeoecology, DOI: 10.1016/j.palaeo.2017.01.036.

- **Comparison of low cost 3D structured light scanners for face modeling.**

Bakirman, T., Gumusay, M. U., Reis, H. C., Selbesoglu, M. O., Yosmaoglu, S., Yaras, M. C., Seker D. Z. & Bayram, B. (2017). Comparison of low cost 3D structured light scanners for face modeling. Applied Optics, 56(4), 985-992. DOI: 10.1364/AO.56.000985.

- **Identification of Late Epigravettian hunting injuries: Descriptive and 3D analysis of experimental projectile impact marks on bone.**

Duches, R., Nannini, N., Romandini, M., Boschin, F., Crezzini, J. & Peresani, M. (2016). Identification of Late Epigravettian hunting injuries: Descriptive and 3D analysis of experimental projectile impact marks on bone. Journal of Archaeological Science, 66, 88-102. DOI: 10.1016/j.jas.2016.01.005.

- **Three-dimensional documentation of Dolni Vestonice skeletal remains: can photogrammetry substitute laser scanning?.**

Jurda, M. Š. & Urbanova, P. (2016). Three-dimensional documentation of Dolni Vestonice skeletal remains: can photogrammetry substitute laser scanning?. Anthropologie, 54(2), 109.

- **Implementation of photogrammetry to the three-dimensional reconstruction of cut marks: an alternative to the Scanning Electron Microscopy.**

Maté-González, M. Á., Palomeque-González, J. F., Yravedra, J., Domínguez-Rodrigo, M. & González-Aguilera, D. (2016): Implementation of photogrammetry to the three-dimensional reconstruction of cut marks: an alternative to the Scanning Electron Microscopy. Poster. European Society for the Study of Human Evolution. September 2016. Alcalá de Henares (Madrid). ISSN 2195-0776 (Print) / ISSN 2195-0784 (Online).

- **Micro-photogrammetric and morphometric differentiation of cut marks on bones using metal knives, quartzite, and flint flakes.**

Maté-González, M. Á., Palomeque-González, J. F., 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 and Anthropological Sciences, 1-12. DOI: 10.1007/s12520-016-0401-5.

- **Assessment of statistical agreement of three techniques for the study of cut marks: 3D Digital Microscope, Laser Scanning Confocal Microscopy and Micro-Photogrammetry.**

Maté-González, M. Á., Aramendi, J., Yravedra, J., Blasco, R., Rosell, J., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017). Assessment of statistical agreement of three techniques for the study of cut marks: 3D Digital Microscope, Laser Scanning Confocal Microscopy and Micro-Photogrammetry. Journal of Microscopy 0, 1–15. DOI: 10.1111/jmi.12575

- **Flint and quartzite: Distinguishing raw material through bone cut marks.**

Maté-González, M. Á., Yravedra, J., Martín-Perea, D. M., Palomeque-González, J. F., San Juan-Blázquez, M., Estaca-Gómez, V., Uribelarrea, D., Álvarez-Alonso, D., Cuartero, F., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017). Flint and quartzite: Distinguishing raw material through bone cut marks. Archaeometry. DOI: 10.1111/arcm.12327.

- **Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones.**

Palomeque-González, J. F., Maté-González, M. Á., Yravedra, J., San Juan-Blázquez, M., García Vargas, E., Martín-Perea, D. M., Estaca-Gómez, V., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017). Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones. Journal of Archaeological Science: Reports 13, 60-66. DOI: 10.1016/j.jasrep.2017.03.033.

- **A new high-resolution 3-D quantitative method for identifying bone surface modifications with implications for the Early Stone Age archaeological record.**

Pante, M. C., Muttart, M. V., Keevil, T. L., Blumenschine, R. J., Njau, J. K. & Merritt, S. R. (2017). A new high-resolution 3-D quantitative method for identifying bone surface modifications with implications for the Early Stone Age archaeological record. Journal of Human Evolution, 102, 1-11. DOI: 10.1016/j.jhevol.2016.10.002.

- **3D image based modelling for inspection of objects with micro-features, using inaccurate calibration patterns: an experimental contribution.**

Percoco, G. & Salmerón, A. J. S. (2016). 3D image based modelling for inspection of objects with micro-features, using inaccurate calibration patterns: an experimental contribution. International Journal on Interactive Design and Manufacturing (IJIDeM), 1-11. DOI: 10.1007/s12008-016-0342-3.

- **Geomatics and Forensic: Progress and Challenges. In Forensic Analysis-From Death to Justice.**

Rodríguez-Gonzálvez, P., Muñoz-Nieto, Á. L., Zancajo-Blázquez, S. & González-Aguilera, D. (2016). Geomatics and Forensic: Progress and Challenges. In Forensic Analysis-From Death to Justice. InTech.

- **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.**

Yravedra, J., Maté-González, M. Á., Palomeque-González, J. F., Aramendi, J., Estaca-Gómez, V., San Juan Blazquez, M., García Vargas, E., Organista, E., González-Aguilera, D., Arriaza, M. C., Cobo-Sánchez, L., Gidna, A., Uribelarrea del Val, U., Baquedano, E., Mabulla, A. & Domínguez-Rodrigo, M. (2017). 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. Boreas, DOI: 10.1111/bor.12224.

- **FLK West (Lower Bed II, Olduvai-Gorge, Tanzania): A new early Acheulean site with evidence for human exploitation of fauna. Boreas.**

Yravedra, J., Diez-Martin, F., Egeland, C. P., Maté-González, M. Á., Palomeque-González, J. F., Arriaza, M. C., Aramendi, J., García Vargas, E., Estaca-Gómez, V., Sanchez, P., Fraile, C., Duque, J., de Francisco Rodriguez, S., González-Aguilera, D., Uribelarrea, D., Mabulla, A., Baquedano, E. & Dominguez-Rodrigo, M. (2017). FLK West (Lower Bed II, Olduvai-Gorge, Tanzania): A new early Acheulean site with evidence for human exploitation of fauna. Boreas. DOI 10.1111/bor.12243.

- **Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones.**

Palomeque-González, J. F., Maté-González, M. Á., Yravedra, J., San Juan-Blázquez, M., García Vargas, E., Martín-Perea, D. M., Estaca-Gómez, V., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017): Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones. Journal of Archaeological Science: Reports 13, 60-66. DOI: 10.1016/j.jasrep.2017.03.033.

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Aceptado: 12 marzo 2017
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Publicado: Junio 2017
Total de citas: 2
Autocitas: 2

Investigaciones donde se ha citado la publicación:

- **Micro-photogrammetric and morphometric differentiation of cut marks on bones using metal knives, quartzite, and flint flakes.**

Maté-González, M. Á., Palomeque-González, J. F., 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 and Anthropological Sciences, 1-12. DOI: 10.1007/s12520-016-0401-5.

- **Flint and quartzite: Distinguishing raw material through bone cut marks.**

Maté-González, M. Á., Yravedra, J., Martín-Perea, D. M., Palomeque-González, J. F., San Juan-Blázquez, M., Estaca-Gómez, V., Uribelarrea, D., Álvarez-Alonso, D., Cuartero, F., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017): Flint and quartzite: Distinguishing raw material through bone cut marks. Archaeometry. DOI: 10.1111/arcm.12327.

- **Assessment of statistical agreement of three techniques for the study of cut marks: 3D Digital Microscope, Laser Scanning Confocal Microscopy and Micro-Photogrammetry.**

Maté-González, M. Á., Aramendi, J., Yravedra, J., Blasco, R., Rosell, J., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017): Assessment of statistical agreement of three techniques for the study of cut marks: 3D Digital Microscope, Laser Scanning Confocal Microscopy and Micro-Photogrammetry. Journal of Microscopy 0, 1–15. DOI: 10.1111/jmi.12575

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- **Micro-photogrammetric and morphometric differentiation of cut marks on bones using metal knives, quartzite and flint flakes.**

Maté-González, M. Á., Palomeque-González, J. F., 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 and Anthropological Sciences, DOI: 10.1007/s12520-016-0401-5.

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Investigaciones donde se ha citado la publicación:

- **On Applications of Micro-photogrammetry and Geometric Morphometrics to Studies of Tooth Mark Morphology: the modern Olduvai Carnivore Site (Tanzania).**

Arriaza, M. C., Yravedra, J., Domínguez-Rodrigo, M., Maté-González, M. Á., García Vargas, E., Palomeque-González, J. F., Aramendi, J., González-Aguilera, D. & Baquedano, E. (2017). On Applications of Micro-photogrammetry and Geometric Morphometrics to Studies of Tooth Mark Morphology: the modern Olduvai Carnivore Site (Tanzania). Palaeogeography, Palaeoclimatology, Palaeoecology, DOI: 10.1016/j.palaeo.2017.01.036.

- **Assessment of statistical agreement of three techniques for the study of cut marks: 3D Digital Microscope, Laser Scanning Confocal Microscopy and Micro-Photogrammetry.**

Maté-González, M. Á., Aramendi, J., Yravedra, J., Blasco, R., Rosell, J., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017). Assessment of statistical agreement of three techniques for the study of cut marks: 3D Digital Microscope, Laser Scanning Confocal Microscopy and Micro-Photogrammetry. Journal of Microscopy 0, 1–15. DOI: 10.1111/jmi.12575

- **Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones.**

Palomeque-González, J. F., Maté-González, M. Á., Yravedra, J., San Juan-Blázquez, M., García Vargas, E., Martín-Perea, D. M., Estaca-Gómez, V., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017). Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones. Journal of Archaeological Science: Reports 13, 60-66. DOI: 10.1016/j.jasrep.2017.03.033.

- **Flint and quartzite: Distinguishing raw material through bone cut marks.**

Maté-González, M. Á., Yravedra, J., Martín-Perea, D. M., Palomeque-González, J. F., San Juan-Blázquez, M., Estaca-Gómez, V., Uribelarrea, D., Álvarez-Alonso, D., Cuartero, F., González-Aguilera, D. & Domínguez-Rodrigo, M. 2017: Flint and quartzite: Distinguishing raw material through bone cut marks. Archaeometry. DOI: 10.1111/arcm.12327

- **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.**

Yravedra, J., Maté-González, M. Á., Palomeque-González, J. F., Aramendi, J., Estaca-Gómez, V., San Juan Blazquez, M., García Vargas, E., Organista, E., González-Aguilera, D., Arriaza, M. C., Cobo-Sánchez, L., Gidna, A., Uribelarrea del Val, U., Baquedano, E., Mabulla, A. & Domínguez-Rodrigo, M. (2017). 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. Boreas, DOI: 10.1111/bor.12224.

- **FLK West (Lower Bed II, Olduvai-Gorge, Tanzania): A new early Acheulean site with evidence for human exploitation of fauna. Boreas.**

Yravedra, J., Diez-Martin, F., Egeland, C. P., Maté-González, M. Á., Palomeque-González, J. F., Arriaza, M. C., Aramendi, J., García Vargas, E., Estaca-Gómez, V., Sanchez, P., Fraile, C., Duque, J., de Francisco Rodriguez, S., González-Aguilera, D., Uribelarrea, D., Mabulla, A., Baquedano, E. & Dominguez-Rodrigo, M. (2017). FLK West (Lower Bed II, Olduvai-Gorge, Tanzania): A new early Acheulean site with evidence for human exploitation of fauna. Boreas. DOI 10.1111/bor.12243.

- **Flint and quartzite: Distinguishing raw material through bone cut marks**.

Maté-González, M. Á., Yravedra, J., Martín-Perea, D. M., Palomeque-González, J. F., San Juan-Blázquez, M., Estaca-Gómez, V., Uribelarrea, D., Álvarez-Alonso, D., Cuartero, F., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017): Flint and quartzite: Distinguishing raw material through bone cut marks. Archaeometry. DOI: 10.1111/arcm.12327

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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 cut marks.**

Yravedra, J., Maté-González, M. Á., Palomeque-González, J. F., Aramendi, J., Estaca-Gómez, V., San Juan Blazquez, M., García Vargas, E., Organista, E., González-Aguilera, D., Arriaza, M. C., Cobo-Sánchez, L., Gidna, A., Uribelarrea del Val, U., Baquedano, E., Mabulla, A. & Domínguez-Rodrigo, M. (2017): 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. Boreas, DOI: 10.1111/bor.12224.

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Investigaciones donde se ha citado la publicación:

- **Assessment of statistical agreement of three techniques for the study of cut marks: 3D Digital Microscope, Laser Scanning Confocal Microscopy and Micro-Photogrammetry.**

Maté-González, M. Á., Aramendi, J., Yravedra, J., Blasco, R., Rosell, J., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017). Assessment of statistical agreement of three techniques for the study of cut marks: 3D Digital Microscope, Laser Scanning Confocal Microscopy and Micro-Photogrammetry. Journal of Microscopy 0, 1–15. DOI: 10.1111/jmi.12575

- **Flint and quartzite: Distinguishing raw material through bone cut marks.**

Maté-González, M. Á., Yravedra, J., Martín-Perea, D. M., Palomeque-González, J. F., San Juan-Blázquez, M., Estaca-Gómez, V., Uribelarrea, D., Álvarez-Alonso, D., Cuartero, F., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017): Flint and quartzite: Distinguishing raw material through bone cut marks. Archaeometry. DOI: 10.1111/arcm.12327.

- **Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones.**

Palomeque-González, J. F., Maté-González, M. Á., Yravedra, J., San Juan-Blázquez, M., García Vargas, E., Martín-Perea, D. M., Estaca-Gómez, V., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017). Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones. Journal of Archaeological Science: Reports 13, 60-66. DOI: 10.1016/j.jasrep.2017.03.033.

- **FLK West (Lower Bed II, Olduvai-Gorge, Tanzania): A new early Acheulean site with evidence for human exploitation of fauna.**

Yravedra, J., Diez-Martin, F., Egeland, C. P., Maté-González, M. Á., Palomeque-González, J. F., Arriaza, M. C., Aramendi, J., García Vargas, E., Estaca-Gómez, V., Sanchez, P., Fraile, C., Duque, J., de Francisco Rodriguez, S., González-Aguilera, D., Uribelarrea, D., Mabulla, A., Baquedano, E. & Dominguez-Rodrigo, M. (2017): FLK West (Lower Bed II, Olduvai-Gorge, Tanzania): A new early Acheulean site with evidence for human exploitation of fauna. Boreas. DOI 10.1111/bor.12243.

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Investigaciones donde se ha citado la publicación:

- **Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones.**

Palomeque-González, J. F., Maté-González, M. Á., Yravedra, J., San Juan-Blázquez, M., García Vargas, E., Martín-Perea, D. M., Estaca-Gómez, V., González-Aguilera, D. & Domínguez-Rodrigo, M. (2017). Pandora: a new morphometric and statistical software for analysing and distinguishing cut marks on bones. Journal of Archaeological Science: Reports 13, 60-66. DOI: 10.1016/j.jasrep.2017.03.033.

- **<u>On Applications of Micro-photogrammetry and Geometric Morphometrics to Studies of Tooth Mark Morphology: the modern Olduvai Carnivore Site (Tanzania).</u>**

Arriaza, M. C., Yravedra, J., Domínguez-Rodrigo, M., Maté-González, M. Á., García Vargas, E., Palomeque-González, J. F., Aramendi, J., González-Aguilera, D. & Baquedano, E. (2017): On Applications of Micro-photogrammetry and Geometric Morphometrics to Studies of Tooth Mark Morphology: the modern Olduvai Carnivore Site (Tanzania). Palaeogeography, Palaeoclimatology, Palaeoecology, DOI: 10.1016/j.palaeo.2017.01.036

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<u>Investigaciones donde se ha citado la publicación:</u>

- **The paleoecology and taphonomy of AMK (Bed I, Olduvai Gorge) and its contributions to the understanding of the "Zinj" paleolandscape.**

Aramendi, J., Uribelarrea, D., Arriaza, M. C., Arráiz, H., Barboni, D., Yravedra, J., Cruz Ortega, M., Gidna, A., Mabulla, A., Baquedano, E. & Domínguez-Rodrigo, M. (2017). The paleoecology and taphonomy of AMK (Bed I, Olduvai Gorge) and its contributions to the understanding of the "Zinj" paleolandscape. Palaeogeography, Palaeoclimatology, Palaeoecology, DOI:10.1016/j.palaeo.2017.02.036.

- **Paleoecological reconstructions of the Bed I and Bed II lacustrine basins of Olduvai Gorge (Tanzania) and insights into early human behaviour.**

Domínguez-Rodrigo, M., Baquedano, E., A., Mabulla, Mercader, J. & Charles Egeland (2017). Paleoecological reconstructions of the Bed I and Bed II lacustrine basins of Olduvai Gorge (Tanzania) and insights into early human behavior. Palaeogeography, Palaeoclimatology, Palaeoecology, DOI: 10.1016/j.palaeo.2017.05.009.