Archaeological and Anthropological Sciences (2024) 16:178
https://doi.org/10.1007/s12520-024-02083-5

RESEARCH

Alteration by natural processes or anthropogenic manipulation? Assessing human skull breakage through machine learning algorithms

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Received: 2 March 2024 / Accepted: 26 September 2024 / Published online: 11 October 2024

Abstract

Bone breakage is one of the most common features in the archaeological record. Fractures occur at different times and are classified as fresh or dry depending on the presence or absence of collagen in the bone. In the study of human remains, the timing of the occurrence of a fracture is of crucial importance as it can sometimes be linked to the cause of death. Types of skull breakage can be classified based on when they occurred, though not all fractures correspond to the expected features. This variability is added to the challenge of working with bones covered in consolidant, which obstructs the bone surface and hinders taphonomic analysis. This is the case of the Txispiri calotte, which was categorized as a skull cup in the early 20th century, though this classification was later rejected in the 1990s. In this study, we used statistics and machine learning (ML) to test the breakage characteristics of one set of skull fragments with fresh fractures, another set with dry fractures, and the Txispiri calotte. For this purpose, we considered the fracture type, trajectory, angles, cortical delamination and texture of each of the individual fractures. Our results show that the 13 fractures of the Txispiri calotte correspond to dry breakage and bear no relation to artificially produced skull cups. This study shows the potential of ML algorithms to classify fresh and dry fractures within the same specimen, a method that can be applied to other assemblages with similar characteristics.

Keywords Forensic taphonomy · Skull cups · Calvaria · Dry breakage · Green breakage · Postmortem

Introduction

Cranial breakage is one of the most frequently studied topics in the taphonomy of human remains. These studies tend to be particularly interested in determining when bone fractures occurred, which might be during an individual's life (*antemortem*), around death (*perimortem*) or after death (*postmortem*) (Wedel & Galloway 2014). The degree of human involvement in fracture generation is one of the priorities of forensic taphonomy applied to archaeology,

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where it can sometimes be associated with the cause of death (e.g., Sala et al. 2015). Humans have left traces on human skulls as the result of a multitude of practices and through a wide variety of forms and techniques, including, occasionally, their transformation into objects (Bello et al. 2011; Cid-Beziez and Pacheco-Romano 1997; Trejo-Mojica 2008). These skulls exhibit anthropogenic modifications such as cut marks, percussion marks, damage from blows, engravings, etc. (e.g., Gresky et al. 2017; Jeunesse 2012). In addition, this manipulation is often found linked to different contexts such as funerary treatments (Bocquentin and Garrard 2016; Esparza-Arroyo et al. 2020; Goren et al. 2001; Rivero et al. 2021; Santana et al. 2015), religious rituals (Domenici 2014; Pijoan et al. 2010), decapitations (Kanjou et al. 2015), human sacrifices (Carter 2012; Pijoan and Mansilla 1997), war trophies (Jacobi 2007; Miller 1994; Ostendorf-Smith 1995; Owsley 1994; Verhoeven 2013), surgeries (Campillo 2007), violence (Campillo 1976; Fibiger et al. 2023; Moreno-Ibáñez et al. 2021; Sala et al. 2015), and/or human cannibalism (Bello et al. 2011; Cáceres et al. 2007; Marginedas et al. 2022; Rougier et al. 2016; Sala and Conard 2016; Saladié et al. 2012; Solari et al. 2012).

These forms of manipulation include the production of skull cups, objects that originated in the Upper Paleolithic and are still used today (Bello et al. 2011; Boulestin and Henry-Gambier 2019). They are made when there is still collagen in the bone (*perimortem*) and once all the soft tissue has been removed through controlled percussion along the cranial perimeter (outer circumference around the widest part of the head, above the ears and eyebrows), in order to separate the lower part of the skull and the face to preserve the calotte (Bello et al. 2011; Marginedas et al. 2020). This process produces a bowl shape that, according to ethnographic sources, may have been used as a drinking cup (Davis 1867; Hocart et al. 1993; Massola 1961; Meehan 1971). At European prehistoric sites, skull cups are primarily found in association with cannibalism events (Bello et al. 2011; Boulestin and Coupey 2015; Boulestin and Henry-Gambier 2019; García-Sanchez and Carrasco-Rus 1981; Jiménez Brobeil 1990; Marginedas et al. 2020; Saladié et al. 2015; Santana et al. 2019). Different uses have been proposed for these prehistoric artifacts based on their shape and context, including drinking vessels, family relics or even war trophies (Bello et al. 2011; Boulestin 2012).

One of the first researchers to link the presence of human calottes in the archaeological record to intentional manipulation in cannibalistic contexts was Weidenreich (1944, 1951). Based on bone breakage, Weidenreich suggested that the skull shapes of Zhoukoutien (Middle Pleistocene; China) were the result of headhunting or war trophies, as well as corpse consumption. However, these studies were dismissed more recently by Boaz and colleagues (2000), who related skull breakage and other modifications on the bone surface to carnivore activity. Similar cases were documented at Modjokerto (Indonesia) (Jacob 1964) and Makapansgat (South Africa) (Dart 1962). These interpretations suggest that the absence of the lower part of the skull and face are an indication of cannibalism and that the resulting calottes are war trophies (Jacob 1972). According to Jacob (1972), interpretations related to the manipulation of calottes and cannibalism in Indonesian fossil remains were inspired by historical and ethnographic sources (Kleiweg de Zwaan, 1914, 1917). This association may have also influenced other contemporary research on skull cups and cannibalism in western Europe (Barandiarán 1952; Obermaier 1916; Ruiz de Gaona 1945).

The occurrence of fractured and scattered bone remains is a common feature in the archaeological record, yet the osteological record taken as a whole does not include much evidence of anthropogenic breakage. Bone breakage characteristics depend on the amount of collagen and fat they contained at the time they were broken (Wedel & Galloway 2014). Although breakage in 'fresh' bones is usually relatively easy to differentiate from dry bone breakage (Villa and Mahieu 1991), not all fractures align with the expected characteristics. In fact, cranial breakage can sometimes give rise to interpretive problems, especially if the fractures are old, affected by post-depositional damage or covered by layers of materials used for conservation and museum exhibition, such as consolidants and varnishes (Baeza and Menéndez 2016; López-Polín 2012), which obscure characteristics of the fracture like the coloration changes along its edges (Ribeiro et al. 2020; Sorg 2019; Ubelaker and Adams 1995; Villa and Mahieu 1991).

The Txispiri calotte is a cranial fragment found in the burial cave of Txispiri-Gaztelu (Gipuzkoa, Spain), along with other bones associated with the same individual, possibly preserving their original position (Armendáriz and Etxeberría 1983; Ruiz de Gaona 1945). The calotte, initially interpreted as a skull cup, was considered part of the grave goods (Ruiz de Gaona 1945). Although its descriptions in the literature are scarce, the study of this specimen has provided several interpretations about its possible anthropogenic manipulation as a skull cup (Armendáriz and Etxeberría 1983; Etxeberría 1990; Ruiz de Gaona 1945). In fact, the main argument in defense of its artificial character was based on its breakage (Armendáriz and Etxeberría 1983). Although Etxeberría (1990) noted that there is no evidence of human activity on the surface of the skull, no proposal has been put forth regarding how the calotte was fractured to end up with such an unusual shape that shares a striking similarity to a skull cup.

The main aims of this study are to identify the taphonomic processes responsible for the breakage of the Txispiri calotte, to discern whether these fractures were produced on fresh or dry bone, and to determine whether this piece bears any signs of human activity. To these ends, we compared the characteristics of the fracture edges of the Txispiri calotte with two sets of fresh and dry skull fractures. In addition, we developed a method that makes use of machine learning (ML) algorithms to explore fracture classification.

Materials and methods

Materials

The skull fragments analyzed in this study come from Txispiri Cave (Bronze Age; Gaztelu, Gipuzkoa, Spain; Ruiz de Gaona 1945), El Mirador cave (Bronze Age; Sierra de Atapuerca, Burgos, Spain; Cáceres et al. 2007) and a burial site from Abric Romaní (19th century; Capellades, Barcelona, Spain).

Txispiri Cave is formed by two galleries that connect to the outside. The archaeological materials come from the main gallery, which is 25 m in length (Galán et al. 2018). The cave was discovered by Telesforo de Aranzadi in 1934, although it was not excavated until 1944 by Ruiz de Gaona (Astibia et al. 1996), who also published its description in 1945 (Ruiz de Gaona 1945). The cultural sequence has been attributed to the Bronze Age (Altuna et al. 1995). Txispiri Cave was exclusively used as a burial site (Armendáriz and Etxeberría 1983) in which human remains, ceramics and other tools associated with the grave goods were deposited (Ruiz de Gaona 1945). According to the descriptions provided by Ruiz de Gaona (1945), the assemblage belongs to a single sedimentary package. Mixed among the materials, Ruiz de Gaona (1945) described a skull cup within the funerary context. The calotte was found filled with soil, bone fragments and ceramic remains. According to the inventory by Armendáriz and Etxeberría (1983), there are a total of 636 human specimens and 27 dental pieces found scattered. These remains belong to at least 14 individuals, including 2 infants and 1 juvenile. Later studies of the skull suggested that the calotte exhibited signs of anthropogenic breakage, such as flaking of the bone cortex on the external face related to blows from the interior to the exterior of the skull (Armendáriz and Etxeberría 1983). However, Etxeberría (1990) later retracted the original attribution with the assertion that the specimen does not show signs of human activity. In addition, the consolidation, soaking or varnishing treatments to which the specimen has been subjected over the years are unknown. The Txispiri calotte is currently stored at the Gordailua Heritage Collection Center (Gipuzkoa, Basque Country, Spain).

El Mirador cave is located on the southern slope of the Sierra de Atapuerca (Burgos, Spain). The 1999 and 2000 excavations yielded a set of human remains in Level MIR4 with direct dates placing it within the Bronze Age (4,400–4,100 cal BP; Cáceres et al. 2007). These remains belong to six individuals (NISP = 148): one eight year old child and five adults aged 20–40 years old found on a pit without faunal remains (Cáceres et al. 2007; Saladié et al. 2015). All of them were intensively manipulated perimortem for consumption (Cáceres et al. 2007). Remarkably, six skull cups were recovered from among the 42 skull fragments (Marginedas et al. 2020; Saladié et al. 2015). The materials from El Mirador cave are deposited in the Burgos Museum (Junta de Castilla y León).

The 19th century burial assemblage from Abric Romaní (Reference Collection) is a set of skeletal remains from the upper levels of the site. These remains were excavated in the 1980s and consist of 56 dry-fractured cranial fragments broken as a consequence of sediment pressure, trampling and the excavation itself. They belong to a minimal number of 18 individuals (16 adults and two juveniles).

Taphonomic modifications

The bone surfaces of the skulls were examined macroscopically and microscopically with a Dino-Lite AD7013MT loupe. Modifications were documented by bone (frontal, parietal and occipital) and facet (anterior, lateral, posterior, superior and interior).

Postdepositional modifications were characterized through the study of dry breakage, trampling, precipitation of manganese and iron oxides, rounding of fracture edges and concretions. Skull breakage is determined by fracture type, trajectory, location, angle, cortical lamination and texture (Evans 1957; Jordana et al. 2013a, b; Sala et al. 2016). Fractures on skulls, either fresh or dry, may be straight, curved, circular, concentric, radial, or a combination of circular and radial in shape (Jordana et al. 2013b; Sala et al. 2016). The fracture trajectory in dry bones tends to stop at unfused cranial sutures; however, in fresh bones, cracks propagate between sutures (Evans 1957; Jordana et al. 2013a; Sala et al. 2016). In cases of violence, fracture location in relation to the hat brim line (HBL) is used as an indicator to differentiate intentional head trauma from accidental falls (Kremer et al. 2008; Kremer and Sauvageau 2009). Dry breakage usually exhibits right angles (±90º), an irregular texture and the absence of lamination of the bone cortex, whereas fresh breakage tends to have acute (130–160º) and obtuse (20–35º) angles, a smooth texture along the fracture edge and lamination of the cortex (Jordana et al. 2013a, b; Sala et al. 2016). Modern fractures on dry bone are lighter in color than the rest of the bone and other older fractures (Ribeiro et al. 2020; Sorg 2019; Ubelaker and Adams 1995) (Villa and Mahieu 1991) (Table 1). All fractures were considered to discern whether any inference could be made regarding the pieces regardless of the condition of the suture fusion, when it was present. Trampling was identified based on the criteria of Domínguez-Rodrigo et al. (2009) as a U-shaped channel with a sinuous trajectory and no apparent orientation, the absence of flakes and the superimposition of striae. Manganese oxide precipitation causes black staining on the bone surface and is identified based on its location as arborescent or massive dendritic (López-González et al. 2006). The staining is caused by bacteria contained in water with a slightly alkaline pH. Iron oxides cause orange or reddish staining associated with iron-rich sediments and oxygenated and biologically active soils (Fernández-Jalvo and Andrews 2016). Water activity in cave contexts also very often affects the surface of bones by rounding fracture edges. The rounding of bone fractures is identified by the loss of bone density and, depending on the strength and constancy of water flows, a greater or lesser degree of rounding may be present (Fernández-Jalvo and Andrews 2016). Finally, calcium carbonate concretions are caused by lime, which results in water and deposits on the remains, covering their surface and giving rise to bone degradation (Karkanas et al. 2000).

Statistical methods

We tested the type of bone breakage present on the Txispiri cranium using a two-step approach with different statistical techniques.

First, we used R (R Core Team 2022) to perform a Shapiro–Wilk test to analyze the normality of the angles of the fracture planes from Txispiri, Abric Romaní and El Mirador cave. This approach indicated that it was necessary to use non-parametric tests because the *p*-value obtained for the El Mirador and Abric Romaní samples was > 0.05 (Txispiri *p*-value = 0.94; El Mirador *p*-value $= 1.462 \times 10^{-10}$; Abric Romaní *p*-value = 0.0033). Thus, we used a Wilcoxon rank sum test for pairwise comparison among samples. The samples were also compared using a boxplot/violin plot that we created with the ggplot2 (Wickham 2016) and ggbeeswarm (Clarke et al. 2022) libraries in R (R Core Team 2022).

Second, we compared the categorical variables of the Txispiri fractures to our comparative data using a correspondence analysis, due to the qualitative nature of the variables recorded. Here we used unsupervised and supervised learning techniques. This type of analysis allowed us to jointly assess the overall morphologies of all the Txispiri cranium fractures simultaneously and compare them with the reference samples. The analysis was performed using the cabootcrs library (Ringrose 2019) in R (R Core Team 2022).

The main problem with using unsupervised methods as correspondence analysis is that they cannot classify each of the fractures independently but rather analyze all the variability in the sample. We therefore implemented supervised learning methods to improve the classification of the samples in keeping with the approximation previously used by Moclán et al. (2023), who trained machine learning (ML) algorithms to classify binary samples like those we were analyzing (i.e., green-fractured vs. dry-fractured bones).

ML algorithms are one of the most powerful methods currently available for the performance of classification tasks (Lantz 2013), and they have started being used quite extensively in archaeological work (Abellán et al. 2021, 2022; Arriaza and Domínguez-Rodrigo 2016; Cobo-Sánchez et al. 2022; Courtenay et al. 2019). The application of these methods is particularly relevant to archaeological work because they serve to evaluate not only quantitative variables but also categorical variables (Domínguez-Rodrigo and Baquedano 2018). In this study, these methods were used following a standard algorithm training procedure with a well-known reference sample that allows us to classify unknown samples (in our case, the fractures of the Txispiri skull). First, we divided the original reference sample into training (70%) and testing subsamples (30%). The models were validated using cross-validation techniques (10-fold CV; 10 repetitions). We evaluated the accuracy values as the estimator of the best models in combination with kappa metric and other values such as sensitivity, specificity, and balanced accuracy. Accuracy denotes the algorithm's success rate in classifying cases, ranging from 0 to 1. A score of 0 indicates a complete failure in classification, whereas a score of 1 represents perfect classification of the entire sample. According to Lantz (2013: 324), "the Kappa statistic adjusts accuracy by accounting for the possibility of a correct prediction by chance alone." The kappa statistic can range from -1 to 1, with values between 0.80 and 1 indicating "very

Table 1 Summary table of skull breakage characteristics

Skull breakage characteristics	Fracture type	Trajectory	Angle	Cortical lamination	Texture	Color change
Dry breakage (postdepositional/ postmortem)	Mostly straight	Fractures stop at unfused sutures	Right	Absence of cortical delamination	Irregular	Lighter color at the edge of the bone fracture
Fresh (perimortem)	Mostly curved, circular, concentric, and radial	Fractures can cross unfused sutures	Acute and Obtuse	Presence of cortical delamination	Smooth	Uniform color of the specimen and fracture edge

good agreement" (Lantz 2013). Additionally, sensitivity and specificity values are crucial for assessing the data provided by accuracy and kappa statistics. Sensitivity measures the proportion of correctly classified positive examples, while specificity measures the proportion of correctly classified negative examples. These are also known as the "true positive rate" and the "true negative rate" (Lantz 2013). Lastly, balanced accuracy addresses this by averaging the true positive and true negative rates (Domínguez-Rodrigo 2018).

For greater certainty, posterior probability values greater than 0.9 were considered (Cucchi et al. 2013).

We used a selection of 11 base learners that are considered to be the best algorithms currently available (Lantz 2013): neural networks (NNET), linear support vector machines (SVMl), radial support vector machines (SVMr), *k*-nearest neighbor (kNN), logistic regression (LG), decision trees using the 5.0 algorithm (DTC5.0), random forest (RF), gradient boosting (GB), Naïve Bayes (NB), linear discriminant analysis (LDA) and partial least squares (PLS).

Then we used ensemble learning techniques to improve the classification of the samples (Dietterich 2000; Opitz and Maclin 1999; Rokach 2010; Sagi and Rokach 2018). A generalized linear model ensemble was trained and three stacked algorithms were also used, i.e., the NNET, RF and GB algorithms. In this case the meta-algorithms were trained using an 11-fold CV method.

All these methods were performed using the 'caret' (Kuhn et al. 2020) and 'caretEnsemble' (Deane-Mayer 2019; Deane-Mayer and Knowles 2019) libraries in R (R Core Team 2022), which facilitate the configuration of the algorithm hyperparameters and provide quick evaluation of the results. We used the same code as that used by Moclán et al. (2023). The R Studio script (RStudio Team 2021) used here to perform the analysis of the Txispiri cranium is available as supplementary material (Supplementary File 1). The complete databases used to train the models and to classify the Txispiri fractures are also included here as supplementary files (Supplementary Files 2).

Results

The Txispiri calotte

The Txispiri calotte comprises part of the frontal bone, the left parietal and part of the right parietal bones and part of the occipital bone (Fig. 1). This surface of the specimen is entirely covered in a layer of varnish from the conservation techniques performed during the 1950s. The frontal bone of the calotte is deformed outwardly because of its separation from the right parietal through the coronal suture. This separation begins on the right side and opens to the sagittal suture, where it continues opening until it divides into two fissures, one perpendicular to the left parietal and the other longitudinal to the right parietal bone (Fig. 2.1a, 2.2a).

A total of 13 fractures were analyzed. The delineation of 23.1% of the fractures was curved and 76.9% straight. The fracture angles were acute in 8% of the sample, straight in 61% and obtuse in 31%. The right angles were mostly located on the parietal bones and the acute and obtuse angles were documented on the frontal and occipital bones (Table 2; Fig. 2.3c, 2.3d). An irregular texture was documented across the surface of all fractures. We did not find fractures crossing the cranial suture or desquamation of the cortical bone (Table 2).

The top surface of the specimen exhibits large clusters of manganese and the interior surface has a dispersion of arborescent manganese, mostly localized on the parietal and the occipital bones (Fig. 2.2b). It should be noted that the examination of the bone surface at the macroscopic and microscopic levels was hampered by the brightness of the varnish, which produced a reflection that prevented the precise observation of other taphonomic modifications. However, a group of randomly oriented striations were observed on the upper part of the skull, probably resulting from trampling or vermiculation produced by roots (Fig. 2.2b). Nevertheless, it is difficult to specify the origin of these modifications. Greyish spots were observed on the left parietal associated with the degradation of the varnish (Fig. 2.2b), as well as a yellowish coloration on both sides of the frontal and parietal areas (Fig. 2.2). A depression was identified on the posterior part of the left parietal, in proximity to the occipital border that could be related to a depressed and healed antemortem trauma (Fig. 2.4e).

El Mirador cave skull fragments

A total of 133 fractures were documented on the frontal, parietal, temporal and occipital bones (Table 2) of the 33 bones studied from El Mirador cave (Level MIR4). The breakage was produced perimortem (fresh) and consisted of 69.2% curved fractures and 30.8% straight. The majority of the fractures had acute angles (78.2%), followed by obtuse (12.8%) and right (9%) angles. There was a great difference between the fractures with smooth (97.7%) and irregular (3.3%) textures. Fracture trajectory through sutures was documented on 11.3% of the fractures, although 88.7% of them did not cross suture lines. Cortical delamination was documented in 56.4% of the fractures and absent in the remaining 43.6%. Finally, no changes were observed in the coloration of the fractures based on the general coloration of the fossils.

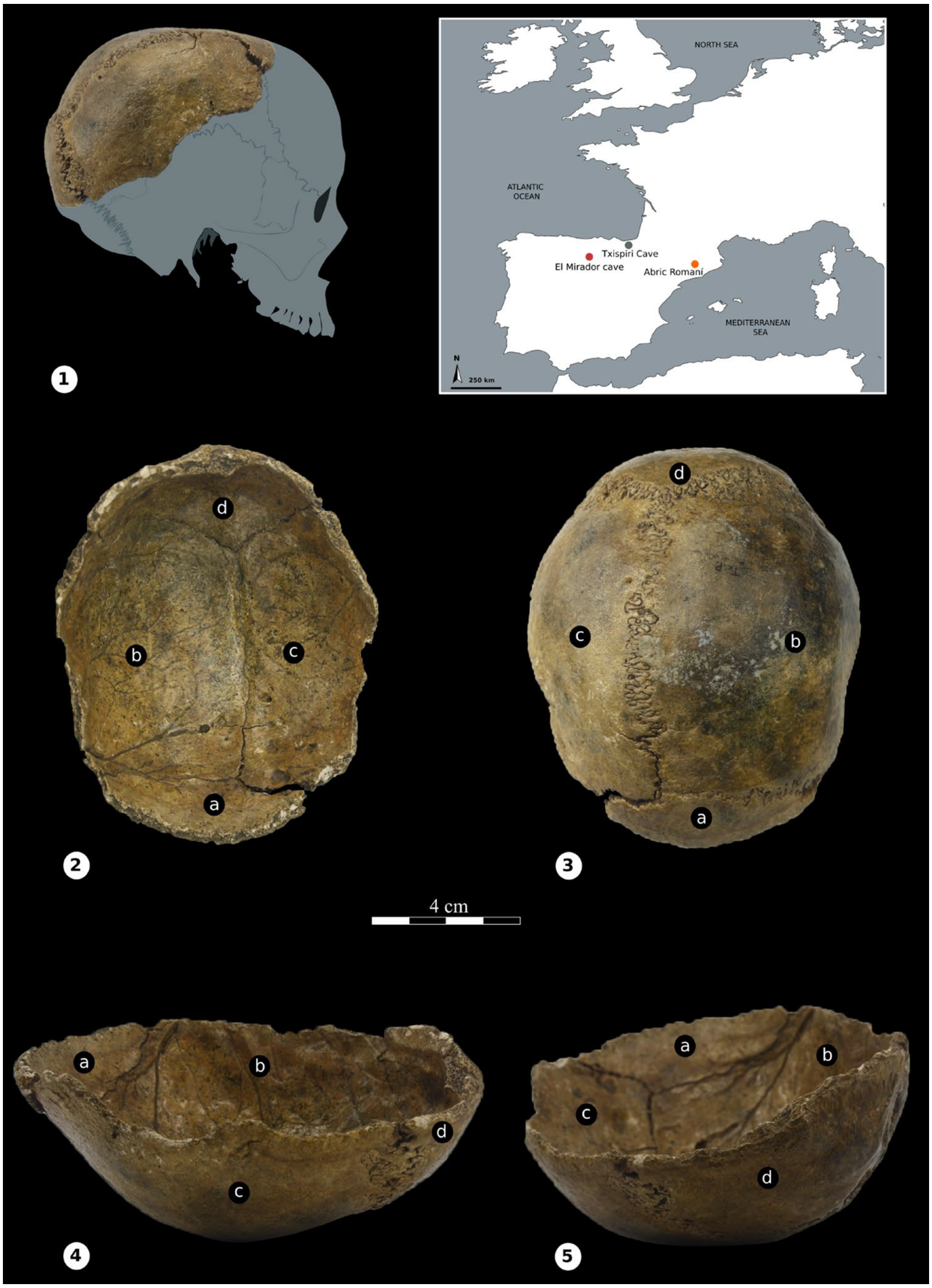


Fig. 1 The Txispiri calotte and location of Txispiri Cave, El Mirador cave and Abric Romaní (1). Interior (2), superior (3), right lateral (4) and latero-posterior (5) facets of the calotte with the bones: frontal (**a**), left parietal (**b**), right parietal (**c**) and occipital (**d**). Credits: The credit for the images of the Txispiri calotte belongs to Francesc Marginedas, to Gordailua Centro de Colecciones Patrimoniales de Gipuzkoa (Diputación Foral de Gipuzkoa) and Centro de Patrimonio Cultural Vasco (Basque Government)

The Abric Romaní skull fragments

The 65 skull fragments with postdepositional and excavation fractures (Reference Collection) from Abric Romaní included 181 fractures distributed among the frontal, parietal, temporal and occipital bones (Table 2). This breakage was produced postmortem (dry) and the fractures were curved in 27.1% of cases and straight in 72.9%. Fracture angles were 9.4% acute, 82.3% straight and 8.3% obtuse. The texture of the fracture edges was 100% irregular. Fracture trajectory across suture lines was present in 6.6% of the samples and absent in the remaining 93.4%. None of the fractures exhibited cortical delamination. Finally, the coloration of the fractures was modified due to the recent breakage during excavation.

Statistics and machine learning

Statistically significant differences ($p < 0.05$; Fig. 2) were found in the statistical comparison between the samples from the reference collection of dry-fractured bones from the Reference Collection and the green-fractured bones from El Mirador cave using the Wilcoxon rank sum test.

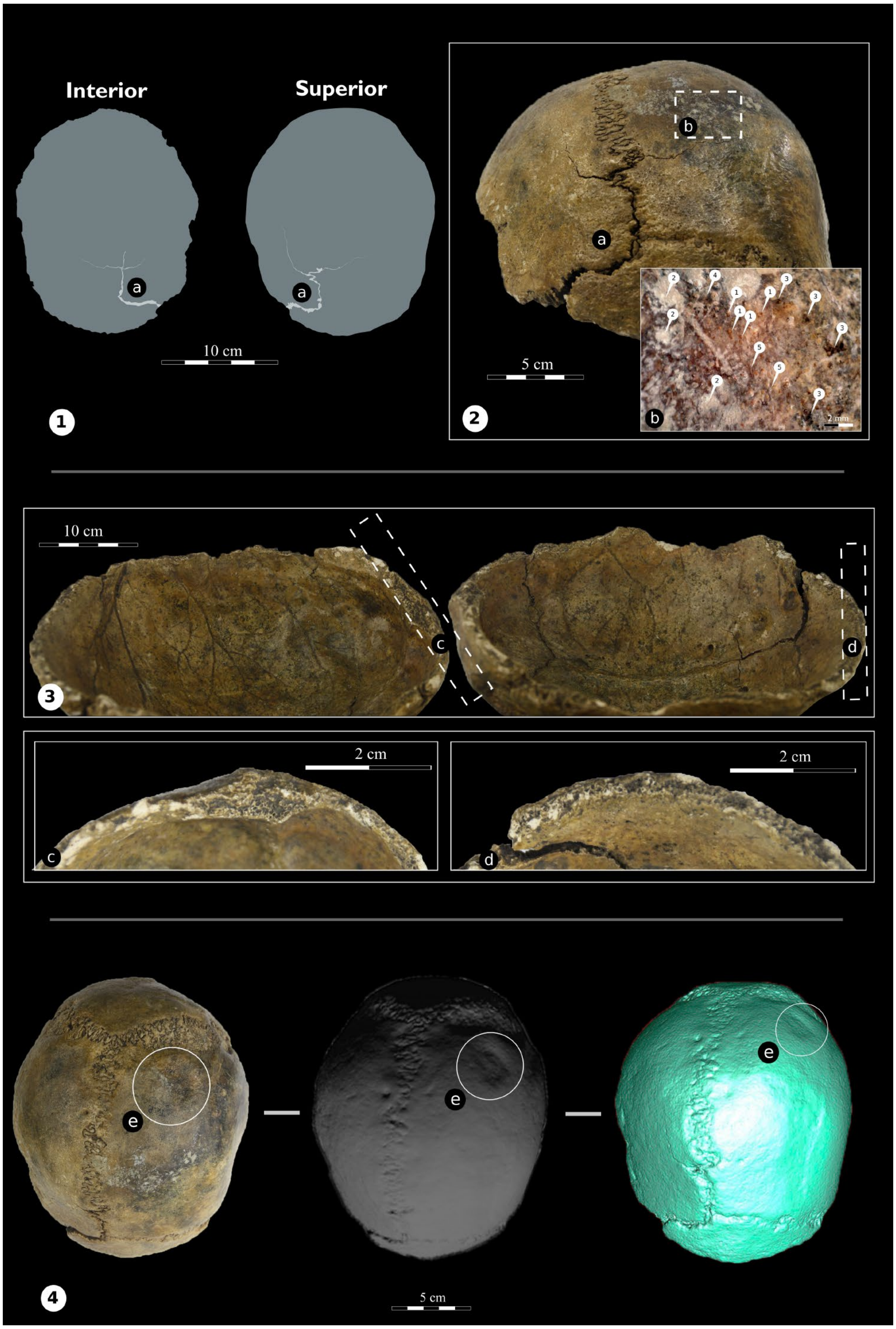


Fig. 2 Taphonomic modifications on the Txispiri calotte. Dry fissures between the frontal and parietal bones and bifurcation at the sagittal suture (**a**). Postdepositional modifications (**b**) such as iron oxidation (b1), varnish degradation (b2), manganese oxidation (b3), possible trampling or roots (b4) and striations on the varnish (b5). The surface of the fracture edges (3) with detail of the fracture of the occipital (**c**) and frontal bones (**d**). Photo of the upper surface of the calotte with the healed depression (**e**) and 3D models with different light sources contrasting the depression. Credits: The credit for the images of the Txispiri calotte belongs to Francesc Marginedas, to Gordailua Centro de Colecciones Patrimoniales de Gipuzkoa (Diputación Foral de Gipuzkoa) and Centro de Patrimonio Cultural Vasco (Basque Government)

The test also suggests statistically significant differences between the Txispiri sample and the green-fractured bones from El Mirador cave, while we cannot reject the null hypothesis when comparing Txispiri with the dry-fractured bones from the Abric Romaní reference collection. These comparisons can also be observed in the boxplot/violin plot (Fig. 2), which shows a significant overlap between Txispiri and the Reference Collection, with El Mirador cave being somewhat below and not overlapping the other two.

The correspondence analysis showed that variables such as irregular texture, right angle, absence of cortical delamination and straight fracture delineation are mostly found on dry fractures (Fig. 3). In contrast, smooth texture, oblique angles, cortical delamination, and curved delineation are characteristics of intentional fresh breakage. The presence

Table 2 Simplified breakage per fracture parameters considered in the study from El Mirador cave, ref. Collection and Txispiri Cave

			Delineation		Angle			Texture		Suture		Delamination	
	Element	Nº Fractures	Curve	Straight	Acute	Right	Obtuse	Smooth	Irregular	Cross	Not-cross	Present	Absent
Txispiri													
	Frontal		1	1	0	2	0	0	2	0	2	0	2
	Parietal		1	7	1	6	1	0	8	0	8	0	8
	Temporal		0	0	0	0	0	0	0	0	0	0	0
	Occipital		1	2	0	0	3	0	3	0	3	0	3
Total (%)		13	**3 (23.1%)**	**10 (76.9%)**	**1 (8%)**	**8 (61%)**	**4 (31%)**	**0**	**13 (100%)**	**0**	**13 (100%)**	**0**	**13 (100%)**
	Frontal		30	15	36	4	5	45	0	3	42	25	20
	Parietal		35	14	42	4	3	49	0	7	42	30	19
	Temporal		6	0	6	0	0	6	0	1	5	5	1
	Occipital		21	12	20	4	9	30	3	4	29	15	18
Total (%)		133	**92 (69.2%)**	**41 (30.8%)**	**104 (78.2%)**	**12 (9%)**	**17 (12.8%)**	**130 (97.7%)**	**3 (2.3%)**	**15 (11.3%)**	**118 (88.7%)**	**75 (56.4%)**	**58 (43.6%)**
	Frontal		14	28	1	38	3	0	42	1	41	0	42
	Parietal		31	72	12	84	7	0	103	9	94	0	103
	Temporal		2	9	0	8	3	0	11	0	11	0	11
	Occipital		2	23	4	19	2	0	25	2	23	0	25
Total (%)		181	**49 (27.1%)**	**132 (72.9%)**	**17 (9.4%)**	**149 (82.3%)**	**15 (8.3%)**	**0**	**181 (100%)**	**12 (6.6%)**	**169 (93.4%)**	**0**	**181 (100%)**
Total		327											

or absence of the fracture trajectory crossing the sutures is clustered in the center of the axis suggesting that this variable carries less relevance. Based on these parameters, the breakage characteristics of the Txispiri calotte correspond to those typical of dry breakage (Fig. 3).

The application of machine learning techniques yielded promising results in relation to bone breakage classification. The hyperparameter configuration is shown in Supplementary File 3. Both base learners and ensembled/stacked models provided high accuracy, sensitivity and specificity values when the test dataset was classified (Table 3). All of the models produced perfect classifications of the test dataset (i.e., accuracy = 1; kappa = 1) except for *k* NN (accuracy = 0.968; kappa = 0.933), NB (accuracy = 0.957; kappa = 0.913) and the ensemble algorithm using a generalized linear model (accuracy = 0.989; kappa = 0.978).

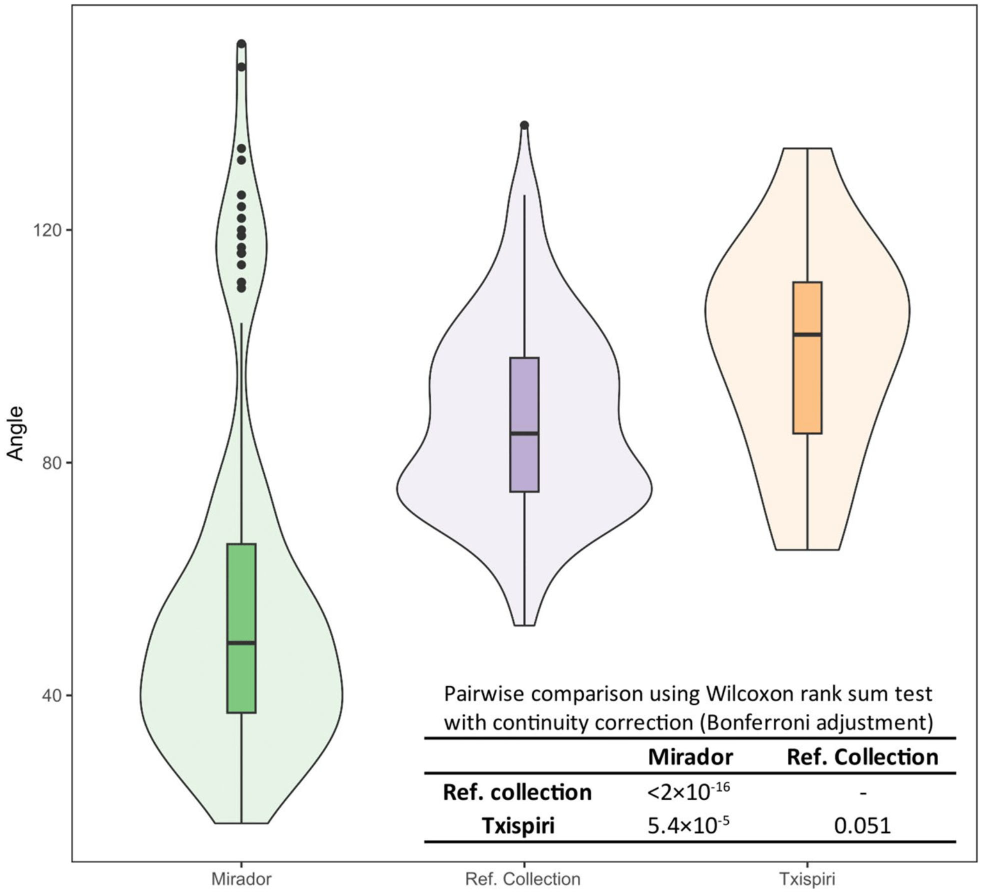
The training process of the ensemble/stacked models is extremely similar to those provided by the base learners, probably due to the high correlation between the base learners (Table 4). However, the correlation between NB and other algorithms is notably low (0.171 to 0.296), which may help to improve the classification performance of the ensemble/stacked models.

The fracture classification of the Txispiri calotte (Supplementary Files 4–5) showed that all 13 fractures analyzed were dry fractures, with one exception which only the NB algorithm classified as fresh (Table 3). Only considering classifications with a posterior classification above 0.9, our results show that all of the samples correspond to dry fractures.

Discussion

The way in which a skull breaks depends on many factors ranging from its stage of decomposition to the agents involved. Taphonomic studies on human remains seek to identify these agents to understand how they affected the bone and to interpret the context in which the breakage occurred, distinguishing between antemortem, perimortem and postmortem fractures (Jordana et al. 2013a, b; Lovell 1997; Ortner 2008; Wedel & Galloway 2014). One of the main purposes of forensic taphonomy applied to archaeology is to study the degree of anthropogenic modifications to cadavers through the study of bone surface modifications (e.g., Robb et al. 2015).

The intentional manipulation of a skull tends to be associated with perimortem breakage, whether in cases of violence, funerary rites, or human cannibalism (Bello et al. 2011; Campillo 1976; Jacobi 2007; Kanjou et al. 2015; Miller 1994; Saladié et al. 2012). In fact, bone breakage is a common feature in the archaeological record and



Pairwise comparison using Wilcoxon rank sum test with continuity correction (Bonferroni adjustment)

	Mirador	**Ref. Collection**
Ref. collection	$<2\times10^{-16}$	-
Txispiri	5.4×10^{-5}	0.051

Fig. 3 Results obtained when comparing angular measurements of fractures using a pairwise Wilcoxon rank sum test (table), a boxplot, and a violin plot from the El Mirador cave skulls, the reference Collection and the Txispiri calotte

Table 3 Results of the ML and ensemble learning algorithms for fresh breakage (El Mirador cave), dry breakage (reference Collection) and the Txispiri calotte. First, the accuracy, kappa, sensitivity, and specificity values provided by the training process of the algorithms are shown in the first seven columns. Then, the classifications of the Txispiri samples are shown in the last four columns, the last two of which have a confidence probability of over 90% for the classification

	Accuracy	Kappa	Acc. Lower	Acc. Upper	Sensitivity	Specificity	Bal. Acc.	El Mirador (fresh)	Reff. Collec (dry)	Fresh ($p > 0.9$)	Dry ($p > 0.9$)
NNET	1	1	0.961	1	1	1	1	0	13	0	9
SVM linear	1	1	0.961	1	1	1	1	0	13	0	13
SVM radial	1	1	0.961	1	1	1	1	0	13	0	13
kNN	0.968	0.933	0.909	0.993	0.923	1	0.962	0	13	0	8
LG	1	1	0.961	1	1	1	1	0	13	0	9
DTC5.0	1	1	0.961	1	1	1	1	0	13	0	13
RF	1	1	0.961	1	1	1	1	0	13	0	12
GB	1	1	0.961	1	1	1	1	0	13	0	9
NB	0.957	0.913	0.894	0.988	1	0.926	0.963	1	12	0	8
LDA	1	1	0.961	1	1	1	1	0	13	0	13
PLS	1	1	0.961	1	1	1	1	0	13	0	0
Ensemble	0.989	0.978	0.942	1	0.974	1	0.987	0	13	0	13
Stacking: NNET	1	1	0.961	1	1	1	1	0	13	0	13
Stacking: RF	1	1	0.961	1	1	1	1	0	13	0	13
Stacking: GB	1	1	0.961	1	1	1	1	0	13	0	9

Table 4 Correlation values obtained by calculating the pairwise correlation of the different algorithms applied to fresh breakage, dry breakage and the Txispiri calotte

	nnet	svmLinear	svmRadial	knn	lg	C50	rf	gb	nb	lda	pls
nnet	1	-	-	-	-	-	-	-	-	-	-
svmLinear	0.880	1	-	-	-	-	-	-	-	-	-
svmRadial	0.813	0.815	1	-	-	-	-	-	-	-	-
knn	0.712	0.672	0.793	1	-	-	-	-	-	-	-
lg	0.880	1	0.815	0.672	1	-	-	-	-	-	-
C50	0.880	1	0.815	0.672	1	1	-	-	-	-	-
rf	0.880	1	0.815	0.672	1	1	1	-	-	-	-
gb	0.813	0.815	1	0.793	0.815	0.815	0.815	1	-	-	-
nb	0.286	0.171	0.296	0.200	0.171	0.171	0.171	0.296	1	-	-
lda	0.880	1	0.815	0.672	1	1	1	0.815	0.171	1	-
pls	0.880	1	0.815	0.672	1	1	1	0.815	0.171	1	1

is particularly common among skull remains. Assessing perimortem and postmortem fractures, however, can be a complex and difficult task (Cappella et al. 2014). Thus, the criterion for discriminating when bone breakage occurred is the amount of water and organic matter (lipids and collagen) retained by the bone (Galloway and Wedel 2014; Kieser et al. 2013; Symes et al. 2014). Most criteria are based on fresh bone biomechanics of mostly complete skulls obtained by forensic medical and experimental studies (Ribeiro et al. 2020). Using fresh bone characteristics as a standard poses a challenge for archaeological research and the study of fragmentary and scattered remains, whose breakage features must be examined independently because both perimortem and postmortem fractures can appear on the same specimen (e.g., Sala et al. 2016). Although distinguishing between fresh and dry breakage is mostly discernible to the naked eye, not all fractures exhibit 100% of the characteristics of each type. In fact, post-depositional processes play an important role in relation to the preservation, decomposition and drying of the bones (Pokines and Baker 2022). Additionally, the observation of these characteristics can sometimes be influenced by bone conservation and preparation treatments (Baeza and Menéndez 2016; López-Polín 2012), which coat the specimen and interfere in the documentation of bone surface modifications. This is the case of the Txispiri calotte, a specimen with marked parallels to skull cup breakage, but of dubious anthropogenic origin (Armendáriz and Etxeberría 1983; Etxeberría 1990).

The statistical study conducted within the framework of this research showed that fracture delineation, angle and texture were telling characteristics which distinguished between perimortem and postmortem breakage in the samples from El Mirador cave (fresh), the Reference Collection (dry), and the Txispiri calotte (Table 2; Fig. 3). We documented higher percentages of straight fractures on dry skulls and the Txispiri calotte, while curved fractures were found on fresh specimens (Table 2). Although more right or oblique angles are generated depending on the state of the bone at the time of fracture, all types of angles occur (Jordana et al. 2013a, b; Sala et al. 2016). In our case, a higher percentage of right angles was found for dry breakage, while fresh fractures exhibited mostly acute and obtuse angles. Notably, almost 40% of the fracture angles on the Txispiri calotte were oblique, which seems significantly high compared to dry breakage (Table 2; Fig. 2). In contrast, high rates of acute angles (78.2%) were documented in fresh breakage in association with blows made from the outside through the cranial perimeter to separate the neurocranium (Fig. 5.5e). Fresh fractures also exhibited angles far above the mean (outliers), a feature poorly represented in dry breakage and nonexistent in the Txispiri specimen (Fig. 2). Texture, on the other hand, can be difficult to measure due to the thickness of skull bones, their sandwich-like structure, and the robustness of the individual. Therefore, we analyzed clear fractures that showed no evidence of postdepositional modifications and found low rates of irregular and high rates of smooth texture for fresh fractures, and 100% irregular textures for dry fractures and the Txispiri specimen.

Cortical delamination is a fresh-related feature that has only been observed in perimortem fractures (56.4%) (Fig. 5.5e). It occurs in the same way as trauma associated with violence or falls, in which an external force strikes the skull (Ribeiro et al. 2020; Sala et al. 2015, 2016). Delamination produced the oblique (acute) angles in the El Mirador cave skull fragments. In contrast, the oblique (obtuse) angles on the Txispiri calotte are unrelated to cortical delamination as previously proposed (Armendáriz and Etxeberría 1983), and therefore are not a sure sign of trauma. Fracture trajectory through unfused sutures is another feature associated with fresh breakage (Jordana et al. 2013b); however this is a functional trait for the study of mostly complete skulls (Sala et al. 2016) and applying this criterion for fragmentary and scattered remains that are not interconnected can be challenging. The comparison between fresh and dry breakage yielded similar proportions of suture crossing, suggesting that this was not a significant variable in this study (Table 2;

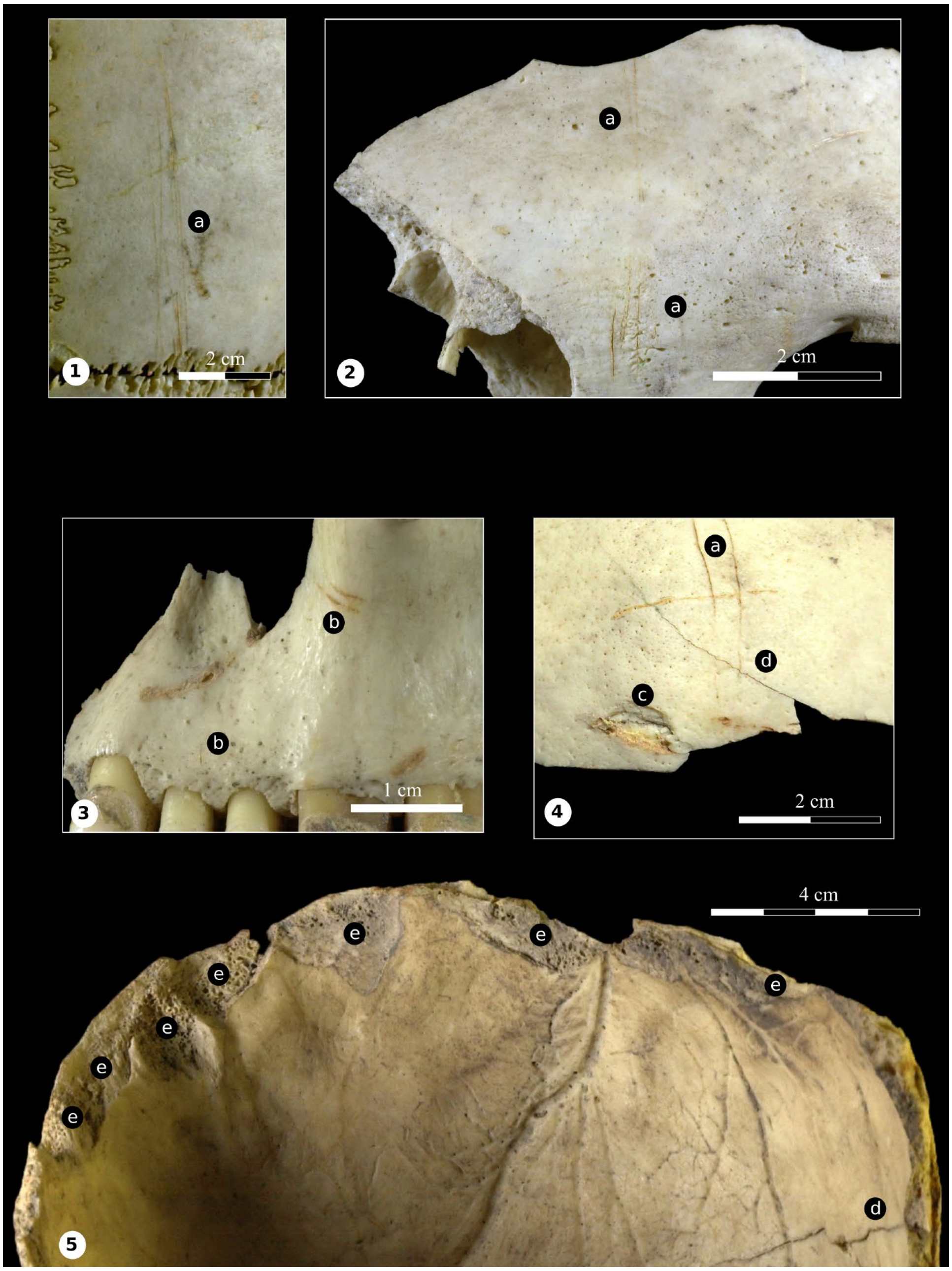


Fig. 5 Anthropogenic activity on skull fragments from El Mirador cave. Cut marks related to scalping (**a**), defleshing (**b**), percussion pits (**c**), fissures (**d**), and cortical delamination (**e**)

Fig. 2). In the case of the Txispiri calotte, none of the fracture trajectories crossed any of the sutures.

No significant differences were found between fresh and dry fracture edges. This indicated that the thicker bones (frontal and occipital) had the same physical breakage characteristics as the thinner bones (parietal and temporal) (Table 2). In addition, one of the most commonly used indicators in distinguishing modern fractures from ancient breakage is a change in coloration between the fracture edge (lighter) and the fossil (darker) (Villa and Mahieu 1991); however, this criterion could not be applied to the Txispiri calotte due to its varnish coating.

Given the few fractures available to study on this specimen, we applied machine learning algorithms to discern the nature of the 13 fractures independently and test their applicability. These algorithms considered features such as delineation, angle, texture, fracture trajectory and cortical bone delamination due to fresh and dry breakage. This method almost perfectly classified all of the fractures as dry breakage, suggesting that natural breakage can produce skull cup like shapes. Only the NB algorithm classified one of the fractures as fresh breakage (Table 3). However, the probability that all fractures were produced in dry conditions exceeded 90% in all of the algorithms.

In addition, the inspection of the surface of the Txispiri calotte supported the absence of human activity suggested by Etxeberría (1990). The presence of modifications such as manganese oxide and a rounded surface (Fig. 4) is consistent with the presence of humidity and water flows of differing intensities after the deposition of the skull. The cementations produced by the presence of humidity alternated with periods of bone desiccation could have played an important role in the breakage of the specimen. This process, in addition to dissolutions and water activity with subsequent drying periods in the cave could have contributed to the breakage of the skull and the partial or total destruction of other bone structures (Karkanas et al. 2000). Additionally, a healed antemortem trauma was documented on the left parietal bone that was most likely related to an intentional strike (Fig. 4.4e). The fact that it is located above the hat brim line may suggest that it was related to interpersonal violence (Kremer et al. 2008).

Despite these results, the morphology of the Txispiri calotte is striking and its resemblance to skull cups is undeniable (Fig. 5). This is because the morphology of skull cups is generally consistent with the breakage of the frontal bone above the supraciliary arches or the frontal eminence. The parietal bones are frequently fractured between the inferior and superior temporalis lines, and the occipital tends to be broken through the occipital plane, above the external occipital protuberance. Nevertheless, some shape variability has been recorded, ranging from a more complete neurocranium to a more pronounced cutout (e.g., Boulestin and Coupey 2015; Santana et al. 2019). Occasionally, a retouching of the edges is visible, probably done in order to standardize the bowl shape (Bello et al. 2011). These retouches are manifested through cortical delamination above the blows produced by detaching the lower part of the skull and the face (Fig. 6.5e). In addition to anthropogenic breakage, other human modifications tend to be noticeable, such as a high frequency of cut marks (Fig. 6) (Marginedas et al. 2020). Indeed, the fact that skull cups were manufactured for a period of at least 15,000 years in European prehistory almost necessarily implies the standardization of these objects. Their representation spans from the Upper Paleolithic of Le Placard (22,000 cal BP; Boulestin and Henry-Gambier 2019) to the Bronze Age of El Mirador cave (4,400–4,100 cal BP; Cáceres et al. 2007; Saladié et al. 2015). Considering the 15 *Homo sapiens* assemblages in which human cannibalism has been recorded to date, skull cups are documented in nine of them (Supplementary File 6). Therefore, they are present in 60% of the cannibalized *Homo sapiens* assemblages identified to date, suggesting that they played a significant and precise role in specific contexts, rather than being used as domestic implements as has been recently proposed (Fernández-Jalvo and Andrews 2021). This is supported by the heterogeneity in skull treatment within these assemblages, some of them with the same chronology and geographic region such as the Iberian Neolithic (García-Sánchez & Carrasco-Rus, 1981; Marginedas et al. 2022; Rivero et al. 2021; Santana et al. 2019; Solari et al. 2012).

In contrast, dry skull manipulation is rare and is usually related to accidental breakage (e.g., Georgieva and Russeva 2016). This is due to the weakness of dry bone in which fractures are not predictable, despite the existence of more fragile areas when the bone is fresh (Wedel & Galloway 2014). Natural breakage of the skull is influenced by multiple factors such as the agents involved, the direction and weight of the applied force, the time of burial and/or subaerial exposure, morphological differences due to age or sexual dimorphism, and pathological anomalies (Jordana et al. 2013a, b; Lieberman 1995). All we know about the recovery of human remains from Txispiri is that they were found 50 cm deep, scattered and mixed with other materials such as lithic industry and ceramics, and probably influenced by water currents (Ruiz de Gaona 1945). Ruiz de Gaona (1945) reported that the assemblage was fragmented

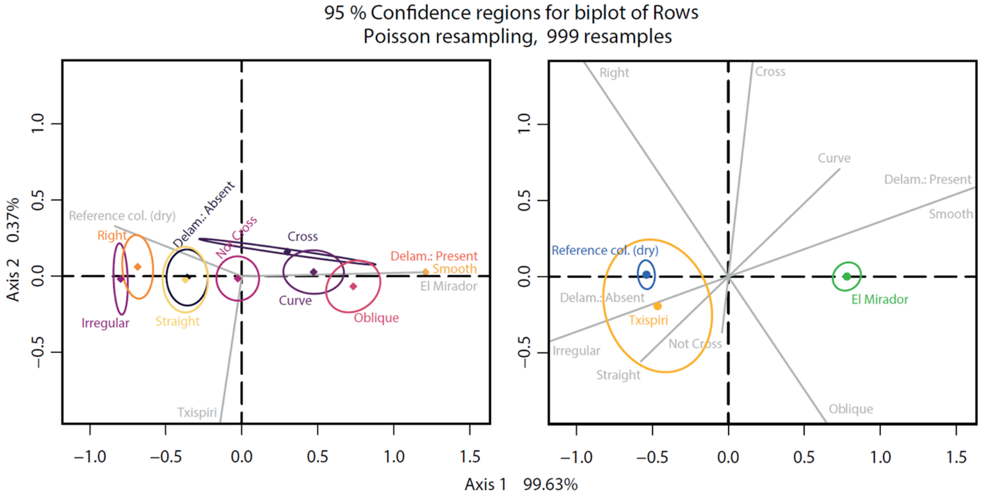


Fig. 4 Correspondence analysis of fresh and dry fractured samples and the Txispiri calotte. Left, 95% confidence interval of the different variables; right, 95% confidence interval of the different analyzed samples

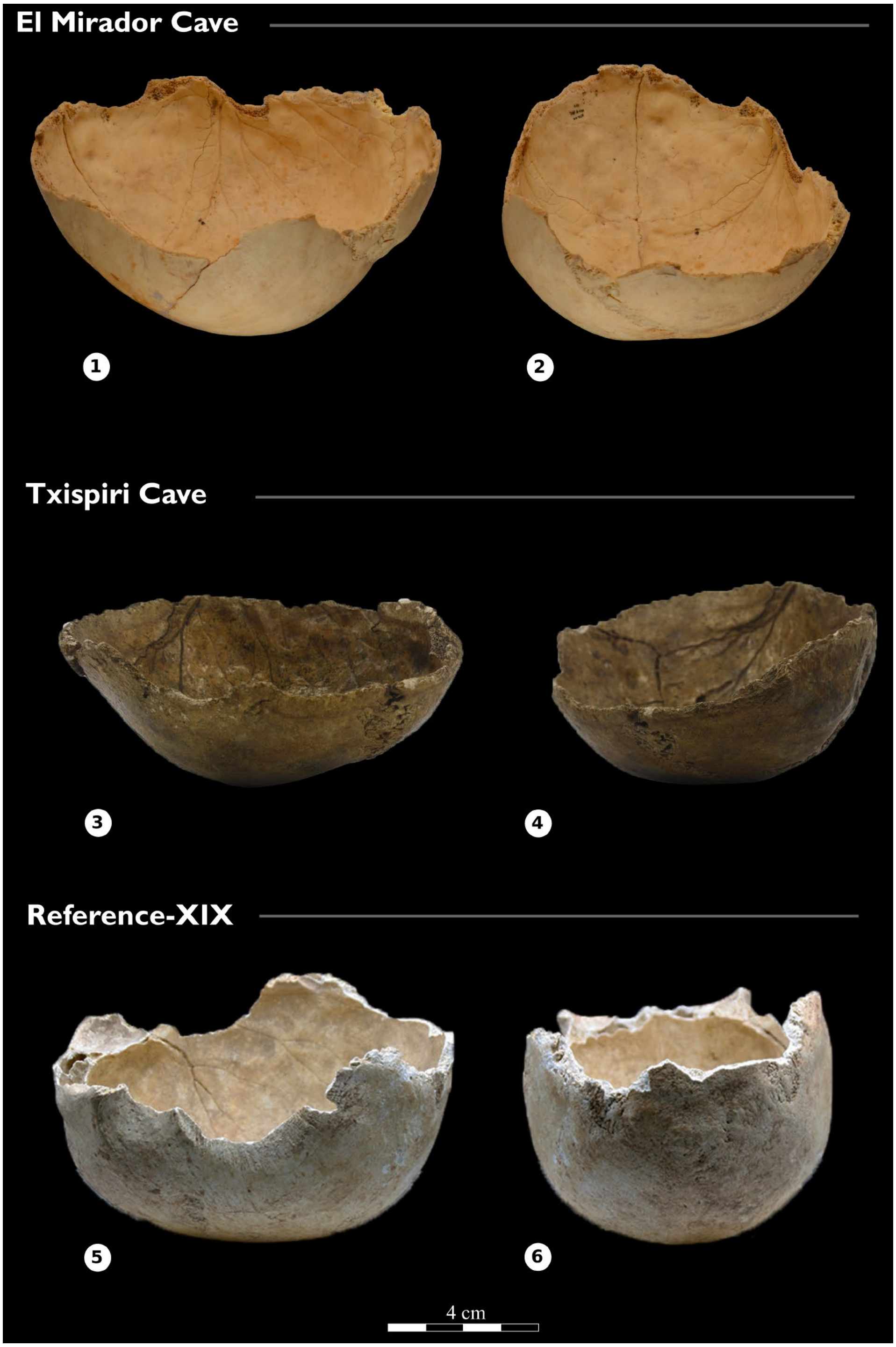


Fig. 6 General morphological comparison between a skull cup from El Mirador cave (**1**, **2**), the Txispiri calotte (**3**, **4**) and a dry fractured calotte (**5**, **6**). Credits: The credit for the images of the Txispiri calotte belongs to Francesc Marginedas, to Gordailua Centro de Colecciones Patrimoniales de Gipuzkoa (Diputación Foral de Gipuzkoa) and Centro de Patrimonio Cultural Vasco (Basque Government). The credit for the images of the El Mirador cave materials belongs to Francesc Marginedas and to the Burgos Museum (Junta de Castilla y León) as the depository of the materials

and mainly consisted of the long bones and the skull with the entire calotte. The preservation of the calotte as a single specimen is sometimes accompanied by the entire frontal bone, including the supraorbital margins. This is a characteristic that is reflected in some Pleistocene specimens (e.g., Lee 2015), some of which were once associated with skull cups and cannibalism (Dart 1962; Weidenreich 1944). However, this morphological feature may be related to the thickness of the cranial vault, which was thicker in archaic humans than in modern humans (Lieberman 1995). It is important to mention that the cutting of the frontal bone on a complete calotte is a rare phenomenon and one that is often present in intentional breakage. In fact, most of the recovered Pleistocene cranial vaults are currently artificially reconstructed with plaster reintegration (e.g., Fernández-Jalvo and Andrews 2019), which reveals that they were highly fragmented in origin. Even so, the natural preservation of the entire neurocranium is not a frequent feature in the archaeological record. In contrast, the breakage of the calotte from Txispiri assumes an entire specimen due to the cutout above the frontal eminence like in skull cups and the same morphological traits documented on the parietal and occipital bones.

The fact that the Txispiri calotte was naturally fractured when dry resulting in a skull-cup-like morphology, reflects the good preservation of this specimen in terms of post-depositional damage. Nevertheless, the study of cranial fractures requires more in-depth studies that examine other variables, especially for dry breakage. Although very few studies focus specifically on the biomechanics of dry skull breakage, it tends to be the most common feature in the archaeological record.

Conclusion

The study of skull breakage can sometimes be problematic due to the high degree of fragmentation and scattering of the fragments across the archaeological surface. The Txispiri calotte is a skull specimen that exhibited questionable fractures that at the time it was recovered led it to be interpreted as a skull cup within a funerary context. Despite its morphological similarities to a skull cup, the taphonomic study of the specimen together with the application of machine learning algorithms have shown that the characteristics of the different individual fractures classify them as the result of dry breakage, and there is no evidence of anthropogenic manipulation of the calotte or its use as a container. This demonstrates that natural dry breakage is capable of giving rise to bowl-shaped skulls and that this morphology is therefore not exclusively artificial. Taphonomic analysis is needed to ascertain the origin of these bones (i.e., natural vs. anthropogenic). In addition, the use of machine learning algorithms has proven suitable for classifying skull fractures, regardless of the presence or absence of common features of recent fractures, such as a change in the fracture edge coloration. This method has potential applicability to other fragmentary assemblages to discern when skulls in the archaeological record were fractured.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12520-024-02083-5.

Acknowledgements We would like to thank our colleague from IPHES-CERCA, Andreu Ollé, for sharing his photos of the skull fragments from level MIR4. We would also like to thank Luis Araus, director of the Museum of Burgos (Burgos, Spain), where the materials from El Mirador cave are deposited; Sonia San José, archaeology technician at Gordailua Centro de Colecciones Patrimoniales de Gipuzkoa (Diputación Foral de Gipuzkoa, Spain) and Centro de Patrimonio Cultural Vasco (Gobierno Vasco, Spain) for facilitating our work during the study of the Txispiri calotte; Aurora Martín director of the Museo de la Evolución Humana (Burgos, Spain); and all the staff working in these institutions. This work was supported by a predoc research grant (FM) (PRE2020-091974) funded by the Spanish Ministry of Universities. The Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA) has received financial support from the Spanish Ministry of Science and Innovation through the María de Maeztu program for Units of Excellence (CEX2019-000945-M). This publication is part of the I+D+I projects PID2021-122355NB-C31 and PID2021-122355NB-C32, funded by MCIN/AEI/10.13039/501100011033 and by ERDF: A way of making Europe. The Agència de Gestió d'Ajuts Universitaris i de Recerca (2021-SGR-01239) and Rovira and Virgili University (2022 PFR-URV-64) also funded this study. AR-H. is supported by the Spanish Ministry of Science, Innovation, and Universities through the Ramón y Cajal grant (RYC2022-037802-I). AGO is supported by a Ramón y Cajal fellowship (RYC-2017-22558) and by the research group IT1485-22 funded by the Government of the Basque Country. MC is supported by a Ramon y Cajal fellowship (RYC2019-026697-I) funded by the Spanish Ministry of Science, Innovation, and Universities.

Author contributions F.M., P.S. and A.R-H. were responsible for conceptualization. F.M. was responsible for the taphonomic analysis, visualization, writing the original draft, and producing all figures. F.M. and A.M. developed the methodological approach. M.C. and A.G-O. provided with materials and revised statistical data. All authors reviewed the manuscript.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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