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ARTICLE / *ARTICLE*

Using Classifications to Identify Pathological and Taphonomic Modifications on Ancient Bones: Do “Taphognomonic” Criteria Exist?

Identification d’agents pathologiques et taphonomiques à l’origine de modifications osseuses à l’aide de classifications : existe-t-il des critères dits « taphognomoniques » ?

L. Corron · J.-B. Huchet · F. Santos · O. Dutour

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Abstract Pathological and taphonomic agents can sometimes produce bone modifications that seem indistinguishable from one another, even to an experienced eye. The aim of this study is to propose a classification system to identify modifications observed on skeletal elements from different environmental and chronological contexts, with similar morphologies but varied aetiologies. Two types of classifications, empirical and statistical, were constructed, tested by two independent observers and compared. This classification system aims to categorise, differentiate and identify pathological and taphonomic bone modifications. In this paper, we identify several taphonomic criteria and propose a new term, “taphognomonic”, to characterise criteria that are specific to particular taphonomic agents. The two classification methods complement each other by providing precise (empirical classification) and reliable (statistical classification) diagnostic criteria. Finally, criteria are highlighted to differentiate pseudo-pathological from pathological bone modifications, the ultimate goal being to reduce the risk of misdiagnosis.

Keywords Palaeopathology · Pseudopathology · Taphonomy · Bone modification · Classification · Taphognomonic

Résumé Certains agents pathologiques ou taphonomiques peuvent être à l’origine de modifications osseuses tellement similaires que même un observateur aguerri ne peut les distinguer. Le but de cette étude est de proposer un outil d’identification d’un ensemble de modifications osseuses de morphologies similaires mais d’étiologies différentes, observées sur des éléments provenant d’environnements et de périodes différents. Deux systèmes de classification, empirique et statistique, ont été construits, puis testés et comparés par deux observateurs indépendants. Ces systèmes classent, différencient et identifient des modifications osseuses d’origine taphonomique ou pathologique. Cette étude a permis d’identifier plusieurs critères taphonomiques et de proposer un nouveau terme, « taphognomonique », pour caractériser des critères spécifiques à certains agents taphonomiques. Les deux types de classification sont complémentaires : ils apportent des critères diagnostiques à la fois précis (classification empirique) et fiables (classification statistique). Enfin, les critères permettant de différencier les modifications pseudopathologiques des modifications d’origine pathologique sont mis en avant, le but ultime étant de réduire le risque d’erreur diagnostique.

Mots clés Paléopathologie · Pseudopathologie · Taphonomie · Modification osseuse · Classification · Taphognomonique

L. Corron (✉)
UMR 7268 ADES, Aix-Marseille université, EFS, CNRS,
Faculté de médecine de Marseille, secteur Nord
51, boulevard Pierre-Dramard, F-13344 Marseille cedex 15,
France
e-mail : louise.corron@etu.univ-amu.fr

J.-B. Huchet · F. Santos · O. Dutour
CNRS, UMR 5199 PACEA,
laboratoire d’anthropologie des populations passées et présentes,
université de Bordeaux, F33615 Pessac cedex, France

J.-B. Huchet
CNRS, UMR 7209, archéozoologie, archéobotanique :
sociétés, pratiques et environnements,
Muséum national d’Histoire naturelle, case postale 56,
55 rue Buffon, F-75005 Paris, France

CNRS, UMR 7205, Institut de systématique, évolution,
biodiversité (ISYEB),
département systématique et évolution (Entomologie),
Muséum national d’Histoire naturelle,
45 rue Buffon, F-75005 Paris, France

O. Dutour
École pratique des hautes études, laboratoire Paul-Broca,
Paris, France

Department of Anthropology, University of Western Ontario,
Ontario, Canada

Introduction

According to Brothwell in 1967 [1], retrospective diagnosis is by far the greatest difficulty in palaeopathology. One of the first challenges is pseudo-pathology. Wells coined this term to refer to "the many conditions which can mimic disease" [2], and which may lead to misdiagnosis by generating "pseudo-pathological" bone modifications. Wells created this neologism for palaeopathological practice, but it does not apply exclusively to this field of study. More recently, Dutour proposed the term "paleopathomimies" [3] to name taphonomic changes that can mimic, sometimes perfectly, pathological conditions observed on dry bones. A growing consensus exists among palaeopathologists to consider pseudopathology as the first diagnostic possibility when observing skeletal remains, whether in archaeological or forensic contexts [3–6].

The mechanisms inducing bone modifications are various; however, the binary response of the bone to numerous stress sources limits the morphological aspects of the lesions to destructive or formative bone anomalies. The main known sources of direct stress on skeletal remains involve different external factors (physical, chemical, biological) that can induce *post-mortem* changes to the bone. Given the extent and impact of these factors, Efremov grouped them together under the term "taphonomy" in 1940 [7], thus creating an entirely new discipline dedicated to the study of these factors and their action on bones. The morphological similarity between taphonomic bone modifications and several types of pathological bone lesions is the main reason for cases of pseudopathology, as demonstrated through historic [8,9] and more recent case studies [10–12]. This similarity is often correlated with local taphonomic factors and excavation conditions [13–16]. Generally, pseudopathology and taphonomy are only mentioned as possible distinct diagnoses or to correct a diagnosis, and then hastily put aside [17,18]. Therefore, despite their relative frequency, there is no reference work on pseudopathological bone modifications.

By studying and comparing pathological, pseudopathological and taphonomic bone modifications, we aim to propose a classification system covering these different types of bone modifications, in order to present and organise criteria that can be used to distinguish between them. This is a stepwise system that presents the different morphological characteristics of bone modifications in order to produce a diagnosis, or at least restrict the list of aetiological possibilities for each type of bone modification observed.

Materials

This study was mainly conducted on two archaeological skeletal samples (Tables 1, 2) taken from two different geographical and chronological contexts [19–21]: the prehistoric sites of Hassi-el-Abiod, Bou Djebeha and Amtal in Mali, and the medieval site of La Granède, in the South of France. Every bone of each individual in the samples was observed in order to discern "bone modifications". A bone modification is defined as any type of bone anomaly that is outside the range of "anatomical normality', and thus excludes discrete traits. Both sites show a higher prevalence of bone-loss anomalies, but the Malian sites have a more diversified bone modification profile, including bone loss, bone formation, and bone deformation (Table 2). Pathologies had already been diagnosed for several individuals from both sites and have been presented in previous studies [21,22]. The bone modifications caused by these pathologies were also included in this study (Table 3). Similarly, extensive skeletal taphonomic analyses had been undertaken for both sites in previous studies [19–22], so the conditions of decomposition and the environmental agents were known.

This sample choice was based on the postulate that the diversity of their geographical areas, chronological periods and environmental contexts could expand the range of morphological variations of the bone modifications.

Table 1 Environmental, chronological, biological and archaeological characteristics of the sites providing the specimens used for the study / *Caractéristiques environnementales, chronologiques, biologiques et archéologiques des sites ayant fourni les éléments osseux étudiés*

	Hassi-el-Abiod, Bou Djebeha and Amtal (Mali) [19–21]	**La Granède (Aveyron, France) [22]**
Chronological period	Mesolithic–Early Neolithic 7500–5000 BP	Medieval 4th–12th century
Environment	Desert, dry	Temperate
Potential taphonomic agents	Insects, rodents, hyenas and other carnivores	Abundant ground vegetation (boxwood and oak), rodents, invertebrates
Soil composition	Sand	Wind deposition, mortar, limestone
Total number of studied individuals	89	51

When comparing the data with palaeopathological and taphonomic reference works [3,4,6,24–30], it was noted that the bone modifications observed did not cover the whole range of possibilities in terms of morphological aspects and causalities. Therefore, it was decided to conduct a study including both the modifications observed directly on the bones from the two contexts (Hassi-el-Abiod, Bou Djebeha and Amtal and La Granède) and bone modifications identified (i.e. diagnosed) and extensively described in the literature [4–6] and in referenced pathological, pseudo-pathological and taphonomic case studies, similar or different to those observed directly in the bones from Mali and France. This allowed us to include bone modifications that were not directly observed in dry bones but were accessible as iconographic data (mainly photographs). These were mostly pathological cases, extensively and precisely described using pathognomonic criteria [4,6], with valid verified diagnoses ensuring the accuracy and positive identification of the bone modifications concerned.

Overall, 165 modifications directly observed on bones and modifications described in 40 case studies from the literature were studied, with a total of 173 types of bone

Table 2 Preservation rates of the individuals presenting bone modifications, type and frequencies of bone modifications observed. The ratio indicates the mean number of bone modifications per individual at each site / *Taux de conservation des individus présentant des modifications osseuses, type et fréquence d'observation des modifications osseuses. Le rapport indique le nombre moyen de modifications osseuses par individu pour chaque site*

	Hassi-el-Abiod, Bou Djebeha and Amtal		**La Granède**	
	Overall	**Ratio**	**Overall**	**Ratio**
Number of individuals showing bone modifications	47	0.53	46	0.90
Bone modifications recorded	160	3.40	43	0.935
State of bone preservation	Poor, fossilised (mineralised) bones		Good	
Types of bone modifications observed	**Bone loss 0.90**	**Bone formation 0.10**	**Bone loss 0.82**	**Bone formation 0.18**
Perforations	0.45		0.42	
Cupules/Notches	0.17		0.00	
Osteolysis	0.18		0.10	
Dendritic/Serpigineous impressions, grooves	0.20		0.48	
Appositions		0.60		0.90
Deformations		0.40		0.10

Table 3 List and prevalence of previously recorded pathological cases for the individuals of Hassi-el-Abiod, Bou Djebeha and Amtal (Mali) and La Granède (Aveyron, France) / *Liste des cas pathologiques et prévalence des pathologies précédemment enregistrés pour les individus des sites Hassi-el-Abiod, Bou Djebeha, Amtal (Mali) et La Granède (Aveyron)*

Hassi-el-Abiod, Bou Djebeha and Amtal (Mali) [21]		**La Granède (Aveyron, France) [22,23]**	
Reported pathologies	**Prevalence**	**Reported pathologies**	**Prevalence**
Osteoarthritis	4/89	Osteoarthritis	9/51
Porotic hyperostosis	2/89	Porotic hyperostosis	2/51
Cribra orbitalia (C.O.)	1/89	*Cribra orbitalia* (C.O.)	15/51 (10/51 bilateral)
SES	2/89	*SES*[a]	2/51
Healed and/or complicated fractures	1/89	Healed fractures	1/51
Osteitis	1/89	Periostitis	5/51
Ankylosis	1/89	Langerhans' cell histiocytosis	1/51
Vertebral dystrophy	1/89	Bone tumour (left maxillary bone)	1/51

SES: Serpens Endocrania Symmetrica

modifications included in the classification system. The data analysed in this study includes detailed descriptions of the bone modifications, which are recorded in a database using criteria with binary and multiple descriptors to characterise them (Matériel supplémentaire 1, disponible en ligne).

Methods

Terminology and Classification Rules: Data Collection

The modifications were analysed following palaeopathological and taphonomic reference works [3,4,6,24–29,31], using *a priori* terminologies and accurate descriptive criteria for each type of bone modification, and an *a posteriori* deductive process used by palaeopathologists to emit diagnoses. By including standard works and methodologies accepted and used as such by the scientific community, this study was able to observe the same standards as other palaeopathological and taphonomic reference studies, thus validating the use of the selected criteria.

In order to avoid confusion and contradictions between palaeopathological and taphonomic terms, a single consensual terminology was created from existing palaeopathological [3,4,6,24–28] and taphonomic terminologies [29–39]. This consensual terminology provided criteria and descriptors for every bone modification (Matériel supplémentaire 2, disponible en ligne) and ensured their accuracy. The bone modifications were analysed using a retrospective deductive approach, as palaeopathologists do when examining skeletal remains [3].

The first step was to identify bone anomalies, using a “naïve” approach [40]. This involved observing and recording each bone and bone modification and their inherent characteristics (criteria and descriptors), and taking contextual factors into account, mainly environmental taphonomy. This allowed objective and complete recordings of the bone modifications. The criteria were organised in the following order in the classifications: macroscopic characteristics of the modification, bony and/or skeletal topography, absence/presence and morphology of associated lesions [3]. Next, the “expert” approach was applied, by means of the deductive reasoning used by palaeopathologists, i.e. inferring the process and the agent responsible for the modifications from their objective observation. This double approach is also applicable to the study of taphonomic bone modifications, e.g. for distinguishing cut-marks from various taphonomic modifications [30]. Measurements, such as bone modification diameters, were taken with a 0.1 mm sliding calliper and the smaller bone modifications were observed using a stereomicroscope.

Empirical Classification

The empirical classification is based on stepwise tree models provided by naturalists, which consists in progressing from one criterion to another, or several others, by single or dichotomous divisions/descriptors, following the same criteria order, until a possible diagnosis can be reached [41]. The use of this type of classification tree seems relatively novel in the field of palaeopathology, and was only found in one reference [3]. It will be subsequently referred to as the “empirical” classification. It follows an *a posteriori* approach, meaning that a diagnosis is made after close observation, description and identification of the bone modifications, thus eliminating several diagnostic possibilities, as a palaeopathologist would do. It allows direct comparison between similar bone modifications caused by different types of agents, showing the morphological proximity between lesions and the decisive criterion or criteria allowing a taphonomic lesion to be distinguished from a morphologically similar pathological or other taphonomic lesion. A diagnosis (pathology or taphonomic agent) is proposed in accordance with the textbook cases and following the objective order of criteria indicated above. No “mixed-type” bone anomalies (third main type of bone pathology process [3]) were identified in this study. Therefore, following the postulate that the two processes are incompatible and that only one of the two would leave observable traces on the bone, we decided to separate the modifications in accordance with the two main pathological expressions of the bone: bone formation or bone loss (Fig. 1). These two groups were then subdivided into five main sub-groups of modification types, thus producing five classification trees (Figs 2–6): two types of bone formation anomalies, deformation (Fig. 2) and substance gain (Fig. 3); and three types of bone-loss anomalies: restricted or extensive alterations (Figs 4, 7), extensive alterations and degradations (Figs 5, 8) and bone fracture or absence of anatomical regions (Figs 6, 9).

Statistical Classification: CART® Decision Tree

The empirical classification was then compared with a statistical classification in order to verify the objectivity of the selected criteria. The CART® algorithm [42] produces classification trees from independent variables (the criteria and their respective descriptors), which in this case are categorical. It can process data with missing criteria, which is extremely useful for archaeological and palaeopathological case studies where data are often missing.

It is important to note that for a statistical classification, a diagnosis needs to be made *a priori* for each case in order to include it. It appears at each node and leaf as the agent most frequently responsible for the modification represented by the corresponding node or leaf. As too many agents were identified in the database to be sufficiently discriminative,

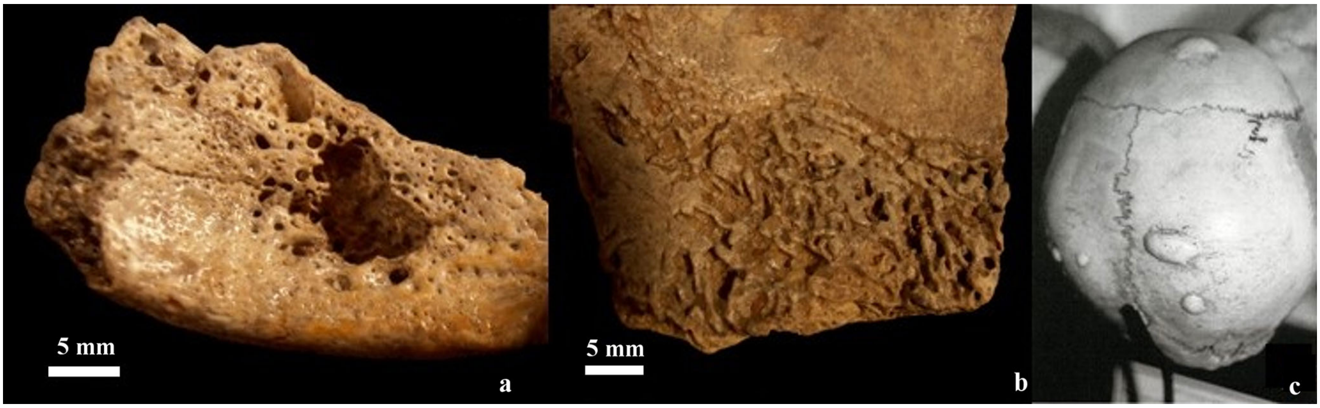

Fig. 1 Examples of bone loss and bone formation. a: advanced bilateral *cribra orbitalia* (Hassi-el-Abiod site, Mali); b: endocranial degradation of the left parietal bone due to a case of *Serpens Endocrania Symmetrica* secondarily eroded by the surrounding sediment (Hassi-el-Abiod site, Mali); c: case of multiple button osteoma (Dupuytren Museum, Paris, Image: Cl. Charon, *In:* Thillaud 1996, p. 189) / *Exemples de perte osseuse et de gain de matière osseuse. a : cas avancé de cribra orbitalia bilatérale (site d'Hassi-el-Abiod, Mali) ; b : dégradation endocrânienne d'un os pariétal gauche due à un cas de Serpens Endocrania Symmetrica secondairement érodé par le sédiment environnant (site d'Hassi-el-Abiod, Mali) ; c : cas d'ostéome en bouton multiple (Musée Dupuytren, Paris, Image : Cl. Charon, In : Thillaud 1996, p.189)*

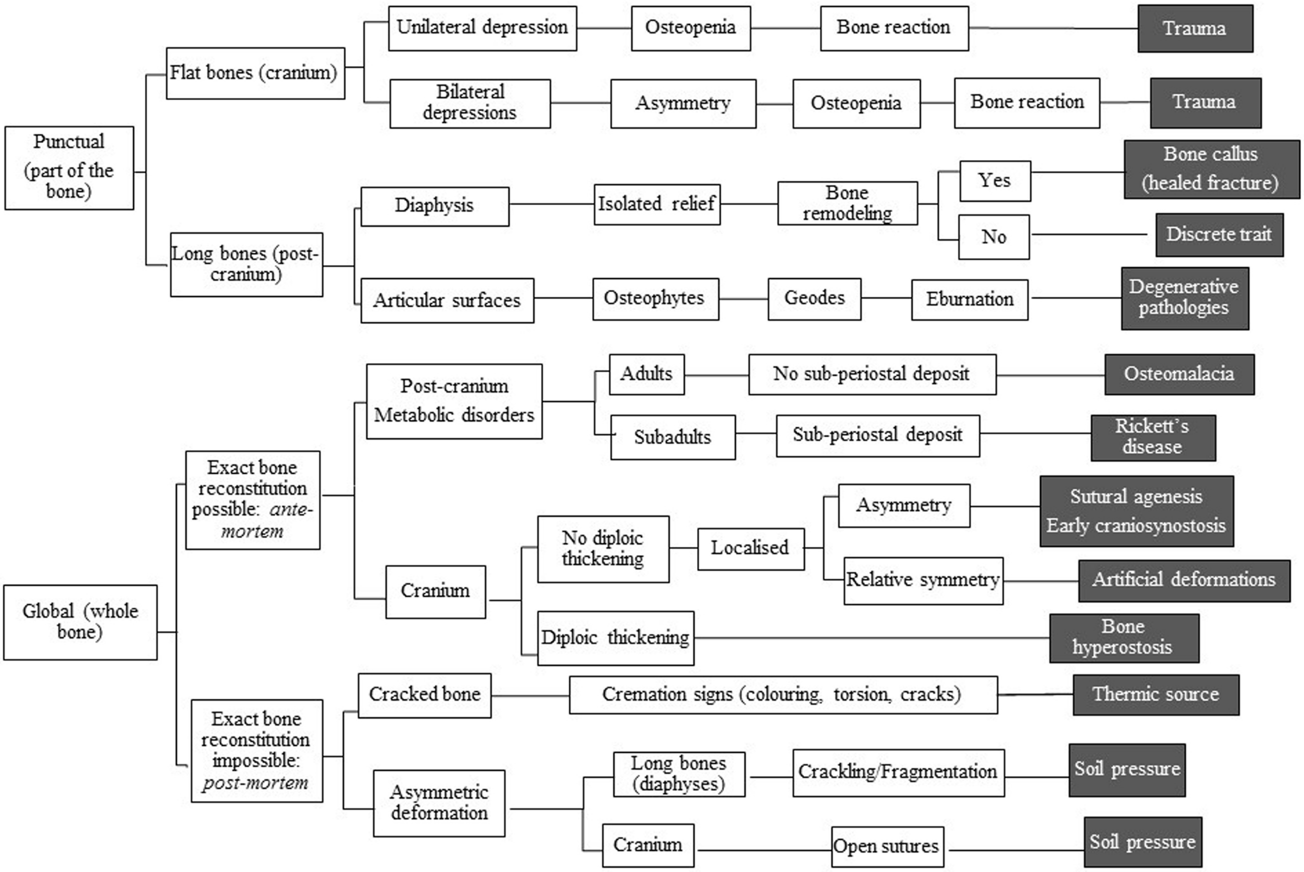

Fig. 2 Bone formation anomalies–deformations. This tree presents the criteria that help to identify several pathologies and taphonomic agents involved in bone deformation. Taphonomic and pathological cases are usually well recognised, as they very often conform to dichotomous criteria / *Anomalies de formation osseuse–déformations. Cet arbre présente les critères d'identification de plusieurs pathologies et agents taphonomiques impliqués dans les déformations osseuses. Les cas taphonomiques et pathologiques sont généralement bien reconnus et respectent souvent des critères d'identification dichotomiques*

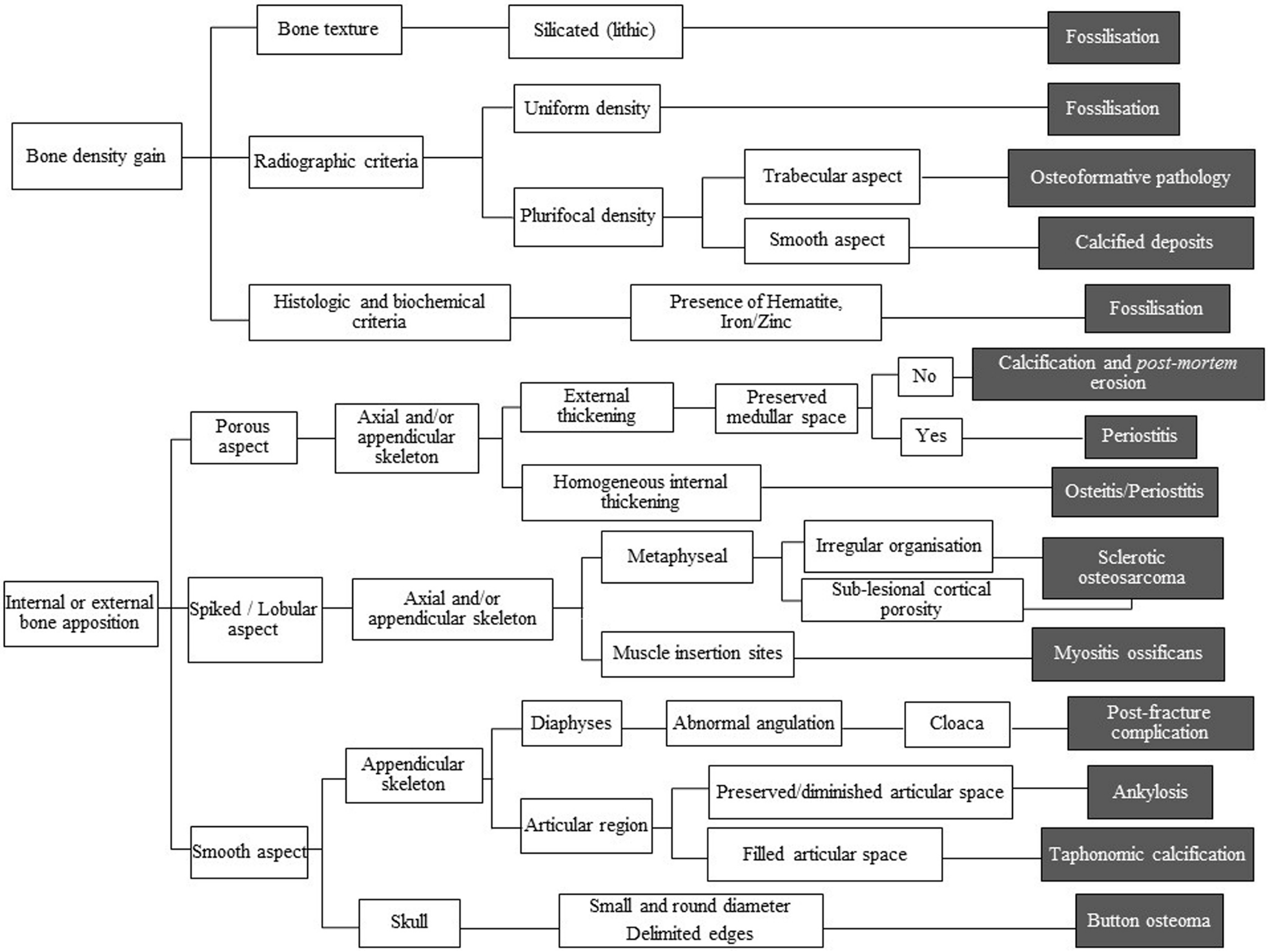

Fig. 3 Bone formation anomalies–gain of bone substance. This tree presents the criteria that help to identify several pathologies and taphonomic agents involved in substance apposition or change in normal bone density / *Anomalies de formation osseuse–gain de substance osseuse. Cet arbre présente les critères d'identification de pathologies et agents taphonomiques impliqués dans l'apposition de substance sur l'os ou un changement de la densité normale de l'os*

we decided to provide a final simplified dichotomous diagnosis as "taphonomic" or "pathological" for each modification. The diagnosis is less accurate but the discriminative power is greater as it groups a larger number of cases in each node or leaf. Based solely on macroscopic observations, it shows which types of modifications are placed in a group, and why. Except for the generalised dichotomy, the same terminology is used for both the empirical and statistical classifications to ensure comparability.

A recursive procedure selects the most discriminative criteria among all the variables, using a successive series of questions (criteria) and answers (descriptors), until the data is split as much as possible. Each splitting decision is illustrated by a node (the discriminative criterion) and its related branches (the descriptors), ending in a leaf (terminal node), along with the proportion of taphonomic and pathological cases per node and leaf. Each observation (bone modification) falls into a single leaf. The discriminative power correlated with the branches decreases as the tree grows. The tree is grown iteratively until all the predictors are used, or until no split can improve the discriminative power. It is then pruned *a posteriori* of certain nodes and leaves, to remain statistically significant. Splitting and pruning are done several times by cross-validation, meaning that the trees are constructed several times for different subsamples of the whole data set until consensual trees are built. The trees produced by the software are then analysed for selection. Because the empirical classification provides accurate diagnoses, the statistical tree(s) presenting an order of discriminative criteria closest to the one in the empirical classification and the highest discrimination value(s) at the nodes was/were the one(s) selected as consistent with an accurate diagnosis. The statistical trees were built with R$^{®}$ Software (v 2.14.1), using the Rpart$^{®}$ package [43].

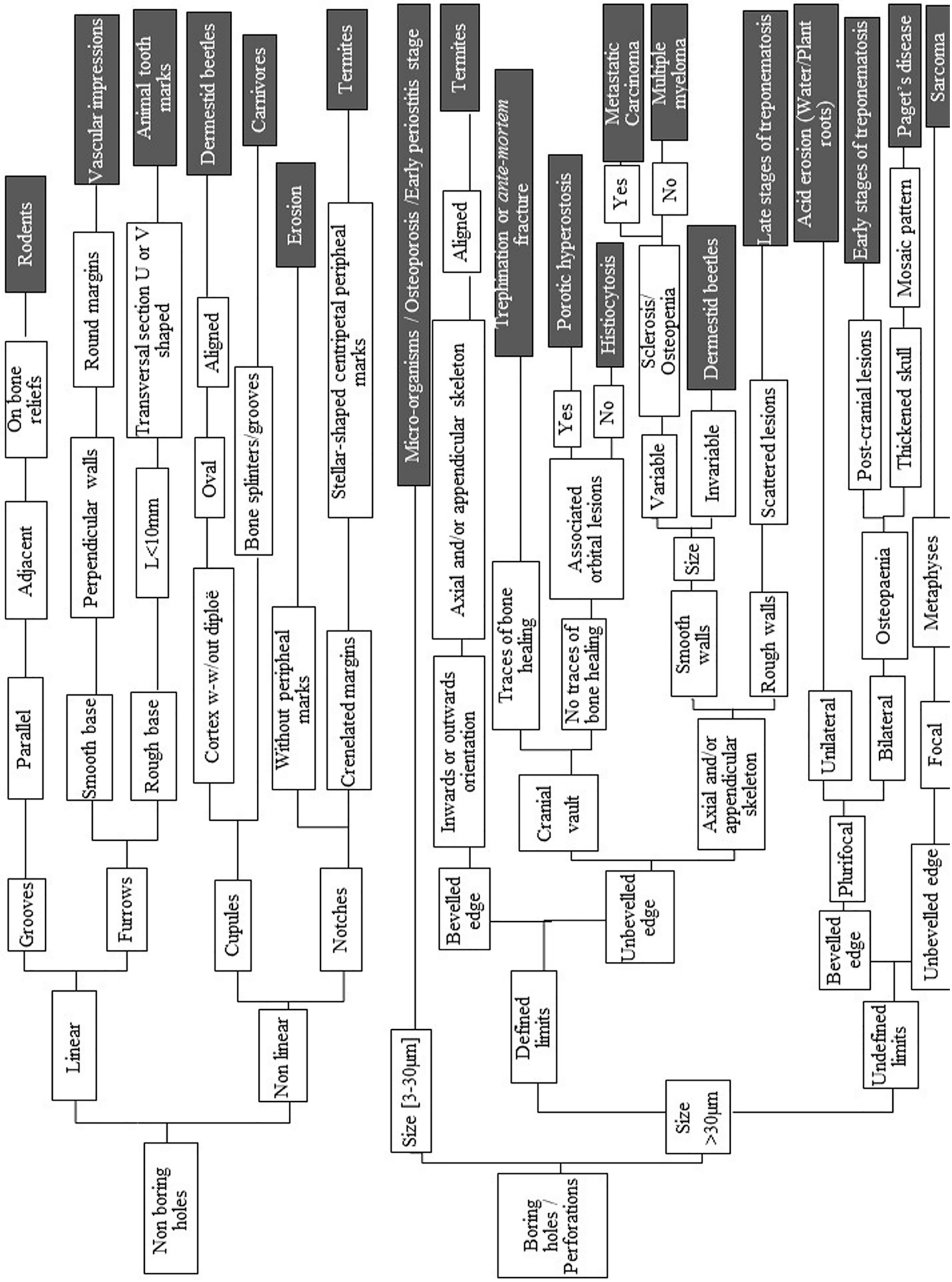

Fig. 4 Bone-loss anomalies–punctual and extensive alterations / *Anomalies de perte osseuse–altérations ponctuelles et étendues*

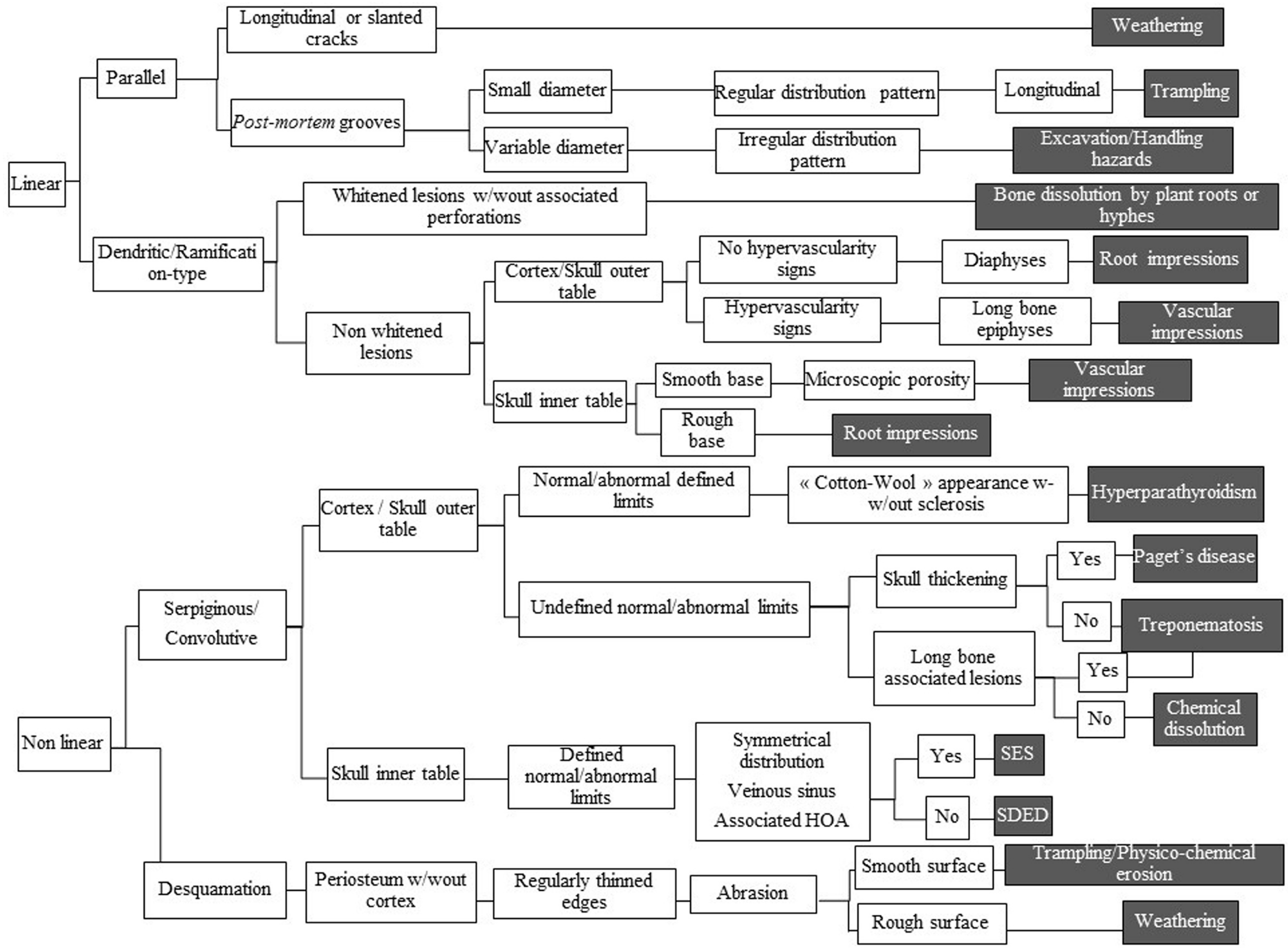

Fig. 5 Bone-loss anomalies–extensive alterations and degradations. *HOA*: Hypertrophic Osteoarthropathy / *Anomalies de perte osseuse–dégradations et altérations étendues. HOA: ostéoarthropathie hypertrophique*

Agreement Rates of the Classification Systems

Intra-observer agreement was part of the construction of the classification: each branch of the tree was constructed after double verification by observer 1 and validation by two experts in palaeopathology (OD) and archaeoentomology (JBH). Inter-observer agreement tests for assessing reproducibility were carried out on 173 photographs of the bone modifications that had been directly observed by observer 1 and by the two experts (OD and JBH) on the bones or in the referenced case reports included in the study. The two independent observers used the empirical and statistical classifications separately to reach a possible diagnosis. Observer 1 had a good knowledge of the classification, whereas observer 2 was independent from the study and had no experience in palaeopathology or bone taphonomy. The empirical classification allowed a single agent per bone modification to be identified as it reached one of the terminal leaves (Figs 2–6). Both observers found a total of 24 different diagnostic possibilities per observed bone modification (23 agents and one "unknown" category). The diagnostic outcomes for each occurrence of the statistical classification (pathological, taphonomic, or unknown) were noted with the letters P, T, or U, respectively. A chi-squared test was performed on the observed numbers of identical diagnoses reached by the two observers using both classifications, to compare them with the theoretical number of agreements necessary for a 95% agreement rate.

Inter-observer agreement for both classification types was statistically tested with Cohen's kappa coefficient [44] to provide an evaluation of the mean agreements reached by the two observers (Table 4). For each type of bone modification, the percentage of agreement between the two observers on a diagnosis or on a taphonomic agent was also calculated (Table 5). All statistical tests were carried out using the R® Software ("psych" package).

The aim of this study being the development of a new methodology, the classification trees are presented as a result and not as a method of study.

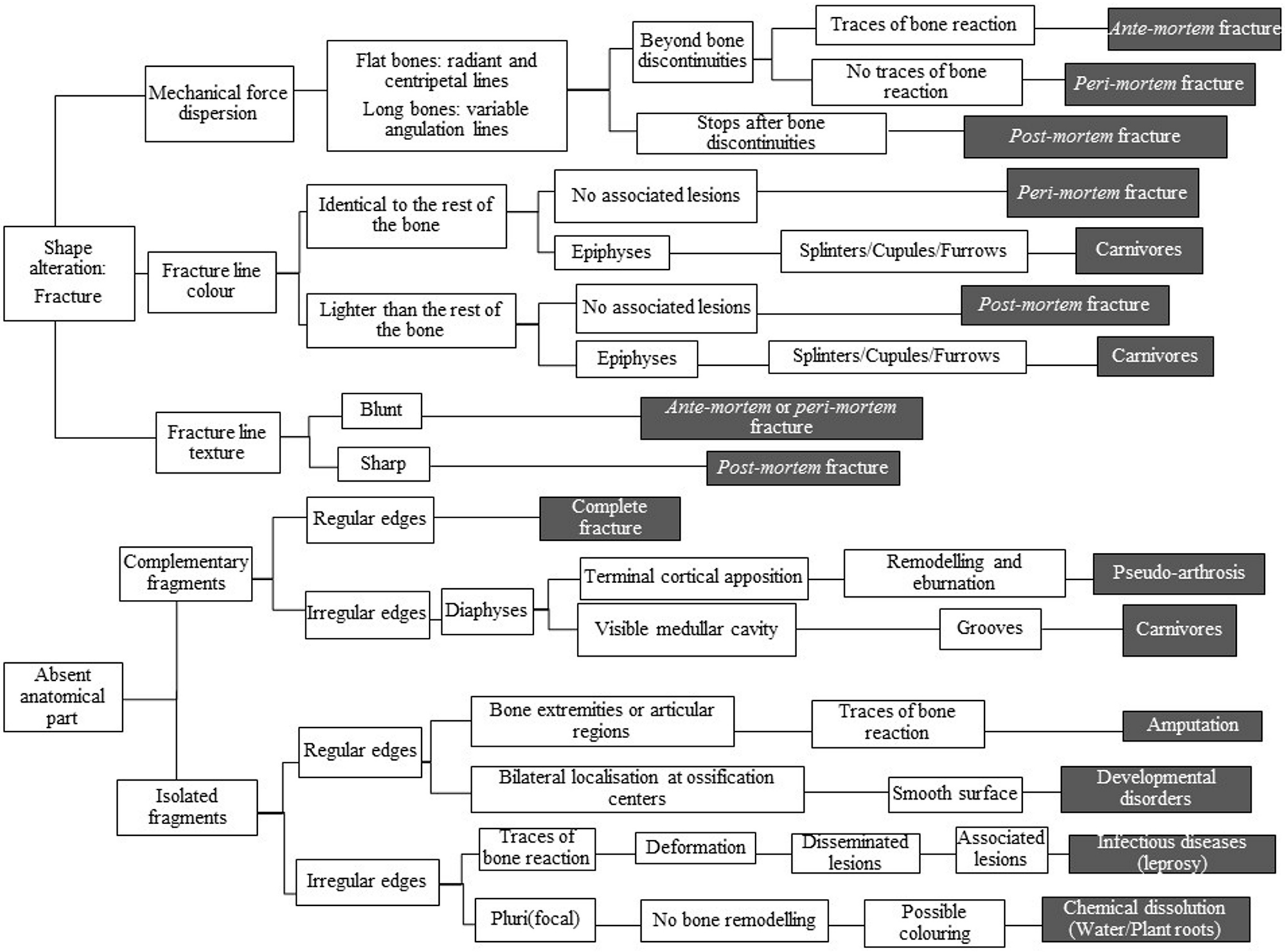

Fig. 6 Bone-loss anomalies–fracture and absence of anatomical bone regions / *Anomalies de perte osseuse–fracture et absence de partie anatomique*

Results and Discussion

More bone modifications were found in the individuals from Mali, with a ratio of modifications per individual higher than 1 (Table 2). The presence and frequency of various bone modifications do not differ greatly between the two samples, illustrating comparable general taphonomic profiles for the two sites (Table 2), whereas, the frequency of certain types of bone modification differs noticeably between the two samples. The skeletal Mesolithic remains from Mali clearly show a higher relative percentage of perforations, cupules and notches ($f = 0.47$), which can be directly linked to the presence of Dermestid beetles and termites. Individuals from La Granède show an equally high relative frequency of perforations and dendritic/serpiginous impressions ($f = 0.46$), which can be directly related to the abundant vegetation present within and near the graves. We therefore have two very explicit examples of the influence of the environmental and taphonomic contexts on bone conservation and palaeopathological interpretations. The general frequency of pathologies is nearly double at La Granède (Table 3). This can be partially explained by a better state of preservation of the individuals from this site, and also by different environmental and historical contexts of the two sites.

Empirical Classification

All the trees in this classification are built up in accordance with the same objective order of consensual criteria leading to accurate diagnoses. They do not, however, take into account rare or unusual bone manifestations of particular pathologies, which do not correspond to these criteria.

Different types of destructive bone modifications can be observed on the same individual. These may also be caused by the same agent (e.g. punctual and extensive bone degradation due to osteophageous termites). The trees are therefore interdependent: they can and must be used together.

Fig. 7 Punctual and extensive alterations: Cupules and perforations. a: cranium in *norma facialis*; b: detail of the anterior side of a left femur; c: detail of the posterior side of a right humerus; d: detail of the anterior side of a left clavicle. Sites AR and MN, Hassi-el-Abiod (Mali) / *Altérations ponctuelles et étendues : Cupules et perforations. a : crâne en norma facialis ; b : détail d'une face antérieure de fémur ; c : détail de la face postérieure d'un humérus droit ; d : détail du bord antérieur d'une clavicule. Sites AR et MN, Hassi-el-Abiod (Mali)*

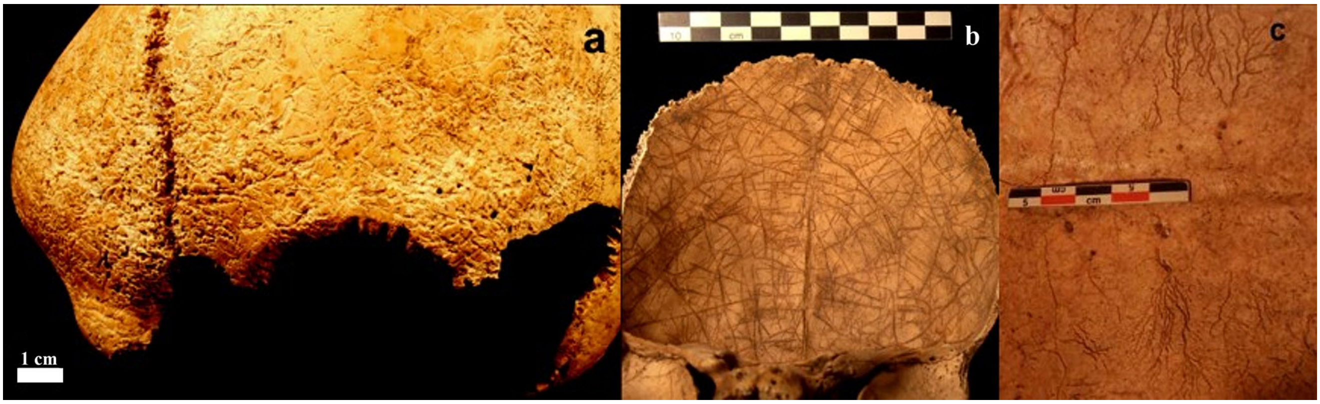

Fig. 8 Extensive degradations. a: Root etchings on the exocranium; b: Traces of roots on the endocranium; c: Vascular imprints of arteriolae on the endocranium. Medieval necropolis of La Granède (Aveyron) / *Dégradations étendues. a : empreintes de racines sur la face exocrânienne ; b : traces de racines sur la face endocrânienne ; c : sillons vasculaires d'artérioles sur la face endocrânienne. Nécropole médiévale de La Granède (Aveyron)*

Bone Formation Anomalies—Deformation (Fig. 2)

Deformation is diagnosed when the intrinsic shape of the bone is modified, resulting in changes in its structure, morphology, volume or contour, without any loss or gain of bony tissue [6]. Pathological bone deformations are often restricted to a limited area of the affected bone (articular surface, relative asymmetry), whereas taphonomic bone deformations usually follow a particular direction on the bone (transversal for the skull and flat bones and

Fig. 9 Example of absence of anatomical parts. Absence of the tuberosity (cortical and spongy bone) of a left radius due to erosion. Site MN, Hassi-el-Abiod (Mali) / *Exemple de l'absence de parties anatomiques. Absence de tubérosité radiale (os cortical et spongieux) d'un radius gauche due à l'érosion. Site MN, Hassi-el-Abiod (Mali)*

Table 4 Statistical tests for assessing inter-observer agreement and correlation between diagnoses of causal agents using the empirical and statistical classifications / *Tests statistiques et taux de corrélation des accords interobservateurs sur l'identification des agents causaux par l'utilisation des classifications empirique et statistique*

Type of classification	Cohen's kappa coefficient	Inter-observer correlation coefficient
Empirical classification	K = 0.462 CI = [0.311–0.613]	0.68 CI = [0.591–0.753] *p*-value = 2.23e-25
Statistical classification	K = 0.68[a] CI = [0.57–0.79]	0.744 CI = [0.668–0.805] *p*-value = 5.06e-31

[a] Unweighted Kappa was used because there are only three modalities (P, T, and U)

longitudinal for long bones). These are due to the physical force of soil pressure, which affects the whole bone, notably the skull, and are often found together with bone fragments that have broken away under pressure. They are therefore strongly related to the geological context, the type of burial and the length of time the remains spent in the soil. Although they are not considered as pathological, they can be mistaken for pathological cases and are therefore included in the classification. There are about as many forms of artificial (cranial) modifications as there are populations who practiced them, but these are relatively well recognised today.

Bone Formation Anomalies—Gain of Bone Substance (Fig. 3)

Several pathologies and taphonomic agents are involved in substance apposition or changes in normal bone density. These cases are diagnosed when a bone is well outside the physiological and anatomical variability of morphology and density.

Surface or medullar substance apposition is usually macroscopically observable and is a sign of many different inflammatory or infectious pathologies and bone tumours [6]. Pathological bone appositions usually follow an anarchic pattern of distribution and ultrastructure, thus illustrating the imbalance between bone formation and bone destruction. They are often found on the sites of bone marrow formation (flat bones and epiphyses). While bone appositions are generally macroscopically observable, a change in bone density often needs to be assessed by medical imaging, histopathological analysis [17,26] or under the microscope, as non-osseous formations will have a different structure to that of bones. Taphonomic processes mainly involve surface appositions (calcifications and concretions) and/or fossilisation and mineralisation of the bones, which explain their unusually high weight and density. This type of modification is strongly related to the geological context, the mineral composition of the soil and the time spent in the soil.

Table 5 Frequencies of the observed bone modifications and agreement rate between observers 1 and 2 by causal agent for each type of bone modification presented in the empirical classification. The values in grey correspond to agreement rates equal to or higher than 0.80 / *Fréquences des modifications osseuses observées dans l'échantillon et taux d'accord interobservateur par type d'agent causal pour chaque type de modification osseuse présenté dans la classification empirique. Les valeurs grisées correspondent à des taux d'accord supérieurs ou égaux à 0,80*

Bone modification	Agent	Sample frequency	Agreement rate
Bone deformation	Discrete trait	2/173	1/2
	Soil pressure	2/173	1/2
Gain of bone substance	Button osteoma	1/173	1/1
Punctual and extended alterations	Carnivores	1/173	1/1
	Cribra orbitalia (associated orbital lesions)	12/173	10/12
	Dermestid beetles	10/173	6/10
	Erosion	12/173	10/12
	Langerhans cell histiocytosis	2/173	0/2
	Porotic hyperostosis	3/173	3/3
	Insects	9/173	9/9
	Micro-organisms	2/173	0/2
	Multiple myeloma	1/173	0/1
	Rodents	19/173	17/19
	Termites	33/173	27/33
Extensive alterations and degradations	Abrasion	2/173	2/2
	Chemical dissolution	6/173	5/6
	Root impressions	20/173	18/20
	Vascular impressions	1/173	1/1
	Excavation hazard	3/173	2/3
	Weathering	14/173	13/14
	Serpens Endocrania Symmetrica (SES)	4/173	3/4
Fractures	*Post-mortem* fracture	2/173	2/2
	Ante-mortem fracture	1/173	1/1

Bone Destruction Anomalies—Punctual and Extended Alterations (Figs 4, 7)

Bone destruction is the main type of anomaly found in archaeological contexts, mostly due to the predominant destructive action of taphonomic agents [30]. Non-extensive alterations are limited in area and are found alone or in clusters. They do not affect the physical and chemical properties of the bone. They are quite easily spotted on a skeleton, but can sometimes be mistaken for supernumerary foramina or discrete traits, depending on their location and size.

One morphological type often correlates to one type of agent (linear = rodents, round = insects) as it reflects the process in action. The differential diagnosis becomes more difficult for more extensive destructive modifications (size > 2 mm). The bone reaction to a destructive pathological process (e.g. sclerosis) or associated lesions can be erased by taphonomic processes once buried in the soil, leaving the modification with a similar morphology to those induced by taphonomic agents. One of the best discriminating criteria in this case is the topographic distribution of the lesions in all the anatomical regions of the skeleton.

Bone Destruction Anomalies—Extensive Alterations and Degradations (Figs 5, 8)

Degradation refers to destructive bone lesions with unclear delimitations that affect the physical and chemical properties of the bone. They are the most problematic types of bone modification and clearly illustrate Boulestin's assertion on taphonomy: single causes must be held as an exception and not as a rule [30]. As in the previous case (Fig. 5), one of the best criteria for identifying the agent responsible is the observed topographic distribution of the lesions, ideally on all the anatomical regions of the skeleton.

Bone Destruction Anomalies—Fracture and Absence of Anatomical Bone Regions (Figs 6, 9)

Fractured bones are systematically found in any archaeological context [3,4]. In most of the cases, they are the result of *post-mortem* breakage of a bone exposed to external forces [30]. *Ante-mortem* fractures are trauma pathologies [4]. Extensive literature is available on the study of fracture mechanisms, particularly on the identification of *ante*-, *peri*-, and *post-mortem* fractures, whether the fracture occurred in fresh or dry bone, and on all the interpretations implied by these parameters [45–47,65]. The fracture line is only dependent on the internal structure of the bone [48] and the type of force exerted on the bone, not on the agent responsible for it [30].

Absence of anatomical parts involves a small range of pathologies, and this stage is rarely attained. The most obvious case in this classification is the loss or total destruction of the missing part after breakage.

Statistical Classification (Fig. 10)

All the statistical trees follow more or less the same order as the empirical trees, which confirms their objectivity. The "best" tree selected here (Fig. 10) includes the highest number of criteria and produces relatively good results in terms of statistical discrimination between different agents responsible for bone modifications. The order followed by the criteria here is morphology, bony topographical distribution, presence/absence of osteopaenia (associated lesions) and skeletal distribution. Because of the requisite binary *a priori* diagnosis, this classification does not highlight pseudo-pathological modifications, which are considered as taphonomic modifications.

Leaf 1 consists mainly of pathological modifications described in the literature and one observed case of parietal button osteoma placed near the sagittal suture of an adult from La Granède.

The cases found in leaves 2 and 3 are exclusively taphonomic. The presence of a bevel is very discriminative in distinguishing between perforations caused by termites, Dermestid beetles [49] and plant roots [5] (leaf 2). Without a noticeable bevel (leaf 3), the orientation criterion is the most discriminating, as leaf 3 does not include pathological modifications. It groups the orientation on the bone and the disposition of the lesions in relation to one another. Pathological lesions are usually distributed more randomly on a particular type of bone (long or flat). Orientation can therefore be considered as a "taphognomonic" factor in the identification of bone modifications.

Distribution symmetry is mainly correlated with pathological cases, but side dominance is not clearly marked (leaf 4).

Osteopaenia can be found with both pathological and taphonomic bone modifications (leaf 5). This sign is normally exclusively related to pathological cases. The restriction to a macroscopic observation level is partly responsible for its attribution to both aetiologies, as the resolution is not high enough to distinguish "real" osteopaenia from taphonomic micro-porosity. The agents that caused the taphonomic cases found in leaf 6 are easily distinguishable by macroscopic or microscopic observation.

Although binary diagnosis decreases the discriminating power of the classification, the similar order of criteria found here validates the objectivity of the criteria and the palaeopathological diagnostic procedure. Most of the bone modifications grouped into the leaves are often distinguishable from each other as the manifestation of different agents, whether taphonomic or pathological. This classification is a useful tool for an initial sorting of bone modifications to determine whether they are more likely to be taphonomic or pathological, according to certain morphological criteria. In order to make it as extensive as the empirical classification and increase its discriminating power, it could benefit from being rebuilt using more occurrences.

Agreement Rates of the Classifications (Tables 4, 5)

For the empirical classification, Cohen's weighted kappa coefficient is equal to $\kappa = 0.462$. The confidence intervals and the Landis and Koch table [50] allow us to state inter-observer agreement as moderate to substantial ([0.41–0.80]). The chi-squared test shows that the observed rate of inter-observer agreement (0.815) differs significantly from the theoretical rate of agreement (0.95), with a standard error of 0.05. The classification still has to be improved to reach the accepted standard level of 0.95 for sufficient methodological reliability. Cohen's kappa for inter-observer agreement is higher for the statistical classification ($\kappa = 0.68$). The confidence intervals and the Landis and Koch table allow us to state inter-observer agreement as moderate to good ([0.41–0.80]).

For both classifications, inter-observer agreement needs to be improved to reach the standard rate of 0.95 (Table 5). Decision trees can be used in clinical or forensic contexts for differential diagnoses [51,52] or to determine ancestry by means of an automated computer-based decision tool [53], with accuracy or performance rates that are comparable to or better than ours. However, we found no study that tested inter-observer agreement, so there is no way of comparing our results to those of other methods.

Inter-observer agreement could very possibly be improved if both observers worked directly on the bones rather than on bone photographs. Associating illustrations with the modifications presented in each terminal leaf of the classifications could provide a visual aid and improve diagnostic accuracy, and therefore diagnostic reliability. The inexperience of observer 2 was valuable for its high objectivity, but probably accounts for the rather low agreement rates. However, because of this inexperience in osteology and palaeopathology, we could consider these rates as the lowest possible and that increasing levels of user experience in palaeopathology

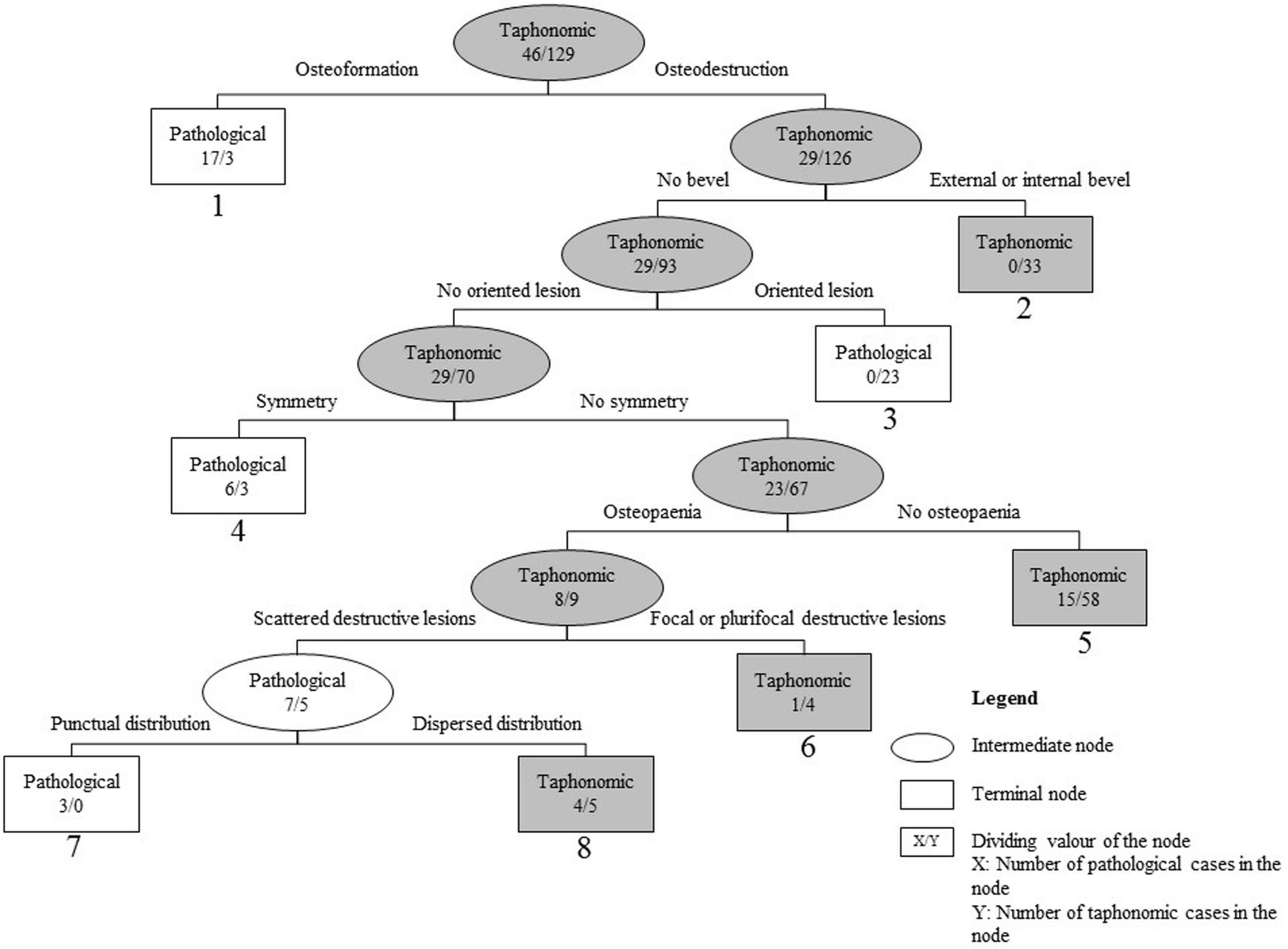

Fig. 10 Statistical classification tree of bone modifications. Leaf 1: Majority of pathological modifications. The three taphonomic cases are calcification and one general and one localised skull deformation due to soil pressure. Leaf 2: The cases include perforations caused by termites, Dermestid beetles and plant roots. Leaf 3: The modifications include rodent tooth marks (parallel grooves), trampling furrows, furrows caused by carnivores, aligned perforations caused by termites and Dermestid beetles. Leaf 4: This leaf regroups SES cases, SDED cases, erosion, some taphonomic perforation cases and dendritic impressions. One pseudo-pathological case is also present: a case of dendritic impressions on the face of a juvenile individual from Hassi-el-Abiod, who also presents a case of skull porotic hyperostosis. Leaf 5: The pseudo-pathological cases included in this group can be easily distinguished macroscopically (cupules, dendritic impressions and perforations). Leaf 6: The pathological case is a growth-related vertebral dystrophia. The taphonomic cases group perforations caused by insects or punctual erosive effects. One pseudo-pathological case is present (destructive porotic modification due to erosion but mimicking early treponematosis). Leaf 7: The pathological cases present here are all *cribra orbitalia*. Leaf 8: The pathological cases include SES, periarthritis, osteoarthrosis and porotic hyperostosis. The taphonomic cases are varied: root etchings, erosion, undetermined modifications, and extensive destruction. The pseudo-pathological cases are serpiginous traces on the skull inner table of a subadult from Hassi-el-Abiod, which seems to be a pathological lesion that was subsequently taphonomised. *SES*: Serpens Endocrania Symmetrica, *SDED*: Sharply Demarcated Erosive Defect / *Arbre de classification statistique des modifications osseuses. Feuille 1 : majoritairement des modifications pathologiques. Les trois cas taphonomiques sont une calcification, et deux déformations crâniennes causées par pression sédimentaire : une généralisée et une locale. Feuille 2 : les cas présents concernent des perforations causées par des termites, des dermestes et des racines végétales. Feuille 3 : les modifications incluent des marques de dents de rongeurs (sillons parallèles), des sillons causés par le piétinement, par les carnivores, et des perforations alignées causées par les termites ou les dermestes. Les lésions pathologiques ont une répartition plus aléatoire sur les os (plats ou longs). Feuille 4 : la symétrie de la répartition est corrélée aux cas pathologiques, mais la dominance n'est pas clairement marquée. Cette feuille regroupe les cas de SES*, de SDED, d'érosion, quelques cas de perforations d'origine taphonomique et des impressions dendritiques. Un cas pseudopathologique est également présent : un cas d'impressions dendritiques sur la face d'un individu immature du site d'Hassi-el-Abiod qui présente également une hyperostose poreuse du crâne. *SES : Serpens Endocrania Symmetrica;*

***SDED : Sharply Demarcated Erosive Defect. Feuille 5 : les cas pseudopathologiques présents dans ce groupe peuvent se distinguer aisément par observation macroscopique (cupules, impressions dendritiques, perforations). Feuille 6 : le cas pathologique présent dans cette feuille est une dystrophie vertébrale développementale. Les cas taphonomiques regroupent des perforations causées par des insectes ou de l'érosion ponctuelle. Un cas pseudopathologique est présent (modification porotique destructive due à l'érosion, mimant un stade précoce de tréponématose). Feuille 7 : les cas pathologiques présents sont tous des cribra orbitalia. Feuille 8 : les cas pathologiques incluent un cas de SES, de la périarthrose, de l'ostéoarthrose et de l'hyperostose poreuse. Les cas taphonomiques sont variés : des empreintes de racines, de l'érosion, des modifications d'origine indéterminée et une destruction étendue. Les cas pseudopathologiques sont des traces serpigineuses sur la table interne d'une voûte crânienne d'un individu immature du site Hassi-el-Abiod. Ce dernier cas semble être une modification osseuse d'origine pathologique qui a été taphonomisée par la suite*

and osteology could only improve them. Thus, we suspect that user experience in palaeopathology and/or taphonomy is likely to be a significant factor of correct or incorrect diagnosis. In this respect, the classification proposed here seems to be an important first step towards proposing a simple but effective and objective tool for an initial sorting of bone modifications to distinguish pathological from taphonomic bone modifications, without necessarily going as far as a precise and unique diagnosis, and therefore allowing the identification of pseudo-pathologies.

Insufficient agreement does not bring the accuracy of the classifications into question, as they are all built on referenced palaeopathological and taphonomic cases with verified diagnoses, and use consensual diagnostic criteria. However, observer agreement does not necessarily mean diagnostic correctness: two observers can agree on a diagnosis but both can be wrong. Also, the diagnoses made by the observers can be biased either by experience or inexperience (knowledge or naivety bias). These biases were considered when developing the objective hierarchical order for the criteria and were the reason for creating the statistical classification. Once again, however, it seems very difficult to bypass these two knowledge-based biases when using and testing the classifications. Despite this, the classification systems remain an innovative and original approach to the study of bone modifications. They need to be put into practice by anthropologists and palaeopathologists, to obtain the necessary feedback for improvement.

Comparison and Limitations of the Classifications

Interestingly, the two classifications give comparable results. Both follow the same general stepwise order of criteria, from the most statistically discriminating (CART®) to the most accurate and precise (empirical) as the trees progress towards a diagnosis. This order was chosen for the empirical classification, as it is related to objectivity and was verified by the statistical tree. Both start by separating bone formation from bone destruction processes. It is intuitively and generally acknowledged that these processes are usually incompatible for the same pathological agent, as a pathological condition results in an imbalance between the two processes (with the exception of "mixed diseases"). This binary response is the only archaeological trace of bone reaction to this *in vivo* imbalance found on skeletonised remains. The cases observed during this study suggest that this binary phenomenon is also a valid criterion for identifying taphonomic agents. The other criteria are used in the following order: type of anomaly, morphological descriptors of the bone modifications, topographic distribution and associated bone lesions. Where the statistical classification only discriminates between taphonomic and pathological modifications, the empirical classification produces a more precise diagnosis, identifying a potential agent and the agents responsible for comparable bone modifications and their diagnostic criteria. The two classifications are therefore validated.

While the general order of the criteria is always maintained, their succession can vary depending on the type of bone modification and the agent responsible, illustrating the stepwise procedure followed for the study of each bone modification. Some of the criteria are known as pathognomonic, i.e. characteristic of a particular pathology. This is true for irregular, disseminated, selected axial distribution and unbevelled perforations caused by multiple myeloma [54]. As a parallel to this, the term taphognomonic seemed suitable to refer to the characteristic criteria for a given taphonomic agent, e.g. irregular, dispersed, and bevelled star-shaped perforations made by termites [23,29,55–59].

In addition to limited bone response to stress factors, several sampling biases are also present. First, the number of cases per type of modification varied substantially (Figs 2–6). This influences the values of the frequencies observed in the statistical classification. These frequencies need to be interpreted in the light of the frequencies found in the sample as a whole. This heterogeneity could also partly explain the relatively low scores obtained for the inter-observer tests. The sample frequencies do not seem to be correlated with the inter-observer agreement rates (Figs 2–6) for each agent diagnosed. Overall, the agreement rate per value ranges from 0 to 100% with a mean 75% agreement rate for all rated modifications, which is much higher than the kappa values but has less statistical significance.

The observation scale was restricted to the macroscopic level, making ultrastructural analysis impossible, and the state of preservation of nearly 10% of the Hassi-el-Abiod sample was too poor for any modifications to be observable. If they were present, they were either hidden or erased by taphonomic processes such as weathering [32,33]. Taphonomy *sensus largo* [7] is largely responsible for the difficulty of observing some of the descriptors and tends to bias the results. As a result, 8% of the bone modifications were not identified as resulting from a specific agent or process.

The discriminating power of the algorithm constructing the statistical classification is limited in two ways: some of the criteria considered as biologically important for a palaeopathologist and used in the empirical classification tables were not necessarily considered as statistically discriminating by the algorithm. This could explain some of the differences between the order of the criteria in the two classifications. Finally, several bone modifications that seem different to an observer are not separated by the software because the corresponding descriptors relate to all of them. However, a macroscopic observation of the cases distributed into the terminal nodes would allow the observer to separate them into homogeneous groups of modification types. They could then be examined and identified using the empirical classification.

As previously mentioned, seemingly similar bone modifications such as pseudo-pathological cases are not always identifiable. There are often several possibilities that need to be considered regarding the identification of the agent responsible for them. This is particularly well illustrated by one type of bone modification examined and identified during this study: serpiginous impressions.

Three destructive modifications (Fig. 11) present similar morphologies that were all grouped into terminal leaf 2 (Fig. 10). All three occurred on the cranial vault, were extensive, disseminated, and present an internal bevel. Close observation allows us to attribute three different diagnoses. The first case (Fig. 11, upper left) is an individual from La Granède presenting Langerhans' cell histiocytosis [60]. The second case (Fig. 11, upper right) results from termites boring into the left temporal bone of a female adult at the Huaca de la Luna archaeological site (Peru) [57]. Finally, the third destructive lesion (Fig. 11, lower left) is due to acid dissolution of the external and internal tables of an adult individual from La Granède. The pathological case was diagnosed by comparison with other lesions with the same morphology and by their particular distribution [60,61]. The second case was interpreted by observing the edges of the lesion, which have characteristic peripheral star-shaped traces [23,57,62] corresponding to the furrows left by the termites' mandibles on the bone surface and the periphery of the perforations [61]. The third destructive modification was identified based on the taphonomic analysis of the individual's position in the grave [22] and the root etchings present all around the destructive lesion.

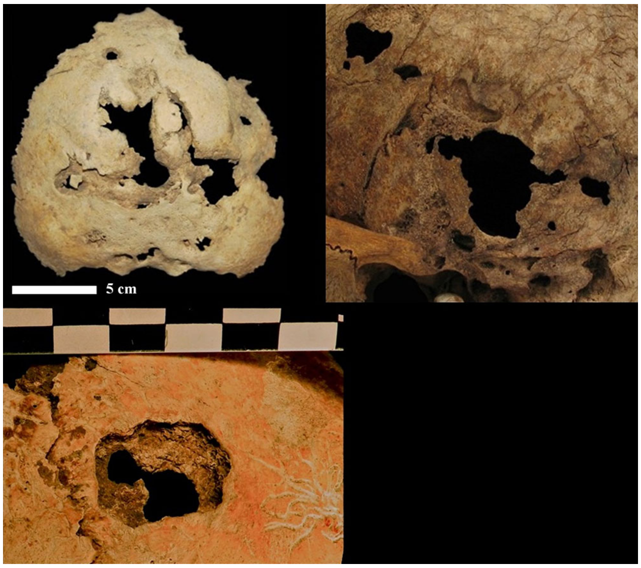

Fig. 11 Three cases of similar bone modifications but with different aetiologies. Upper left: Langerhans' cell histiocytosis; Upper right: termite boring; Lower left: acid dissolution by plant roots / *Trois cas de modifications osseuses similaires mais d'étiologies différentes. En haut à gauche : histiocytose langerhansienne ; en haut à droite : comportement ostéophage de termites ; en bas à gauche : dissolution acide par des racines végétales*

Conclusions

This investigation into the question of pseudo-pathological bone modifications has led to a broader and more complex study of bone modifications in general and to the necessity of considering that any type of process may be involved in their formation.

The use of algorithms such as CART® emerges as a promising means of building bone modification classification trees. However, their discriminative power is still not sufficient to provide a precise diagnosis. The classification systems obtained and used in this study are an example of objectivity (statistical classification) *versus* accuracy (empirical classification). As the former is similar to the latter in its organisation, and the selected criteria are considered as leading to accurate diagnoses in palaeopathology and taphonomy, it is safe to say that they can be used for the study of unknown bone modifications. The sole condition would be that their macroscopic appearance corresponds to one of the types presented here. This type of classification is useful for "non-experts" in palaeopathology but with experience in osteology, (e.g. bioarchaeologists and forensic anthropologists) to analyse bone modifications objectively and exclude diagnostic possibilities, more specifically pseudo-pathologies, and is therefore worth developing and improving further. Until the classification is optimised, the expertise of palaeopathologists is still the best diagnostic tool, provided their findings remain as objective as possible.

The bone modifications observed in the study sample were used directly to build the classification system. A more extensive sample of bone modifications could contribute to the creation of a palaeopathology database that could be used as a reference for anthropologists or palaeopathologists needing to diagnose an ambiguous bone lesion. Also, for complete validation, the classification should be used by different observers and/or experts and applied to an independent validation set of referenced bone modifications of known and certain aetiology.

A palaeopathological study demands as much information as possible to reach a diagnosis. It is tricky to give sufficient weight to information about context for it to be considered as a discriminatory criterion in the statistical classification, which is why it has to be completed with the empirical classification. It is essential to undertake this type of study from a multidisciplinary angle and to consider all the information the site has to offer—the architecture and surroundings of the grave the individual was found in, bone and skeletal taphonomic analyses—to understand the processes and conditions of decomposition, immediate and more general environmental conditions and agents and the general health status of the population before concluding on the aetiology of bone modifications. All of the above parameters play a key-role in the analysis, as they often hold part of the answers to our questions. Nevertheless, close observation of bone modifications is needed to issue a possible diagnosis and even then, great caution is necessary [6].

The important part played by taphonomic bone modifications has led us to consider three different diagnostic possibilities in this study: pathological/pathological, pathological/taphonomic, and taphonomic/taphonomic. The study of bone modifications should therefore include bone taphonomy and pathology, but also skeletal taphonomy (mainly decomposition conditions), not as separate components but as part of the diagnostic toolbox. Elements of the biological profile of an individual and of the immediate or surrounding environment can also be used as diagnostic criteria [63,64].

Finally, this study has proved that the action of taphonomic and pathological agent on bones can both be identified by following the same process: using a precise *a priori* terminology and an *a posteriori* approach. This has led to the proposal of the term “taphognomonic” to characterise the bone modifications that offer descriptive criteria specific to a particular taphonomic agent, action or factor such as those presented here.

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Conflicts of interest: None.

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