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Impacts of curatorial and research practices on the preservation of fossil hominid remains

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Summary - *Fossil remains are the only physical evidence of past forms of life which researchers can use to study the evolutionary biology of a species, especially regarding the human lineage. We review and consider the way in which the conditions surrounding a fossil's discovery and its use for scientific research impacts its long-term preservation. The deterioration of the body starts soon after death, continues in the sediments and only a subsample of the anatomical elements will persist and may finally be unearthed by archeologists. From their recovery onwards, fossil remains are exposed to many sources of further damage: from handling, restoration, measuring to invasive sampling. On the one hand, curators are faced with the inherent challenge of balancing their responsibility to protect fossil specimens with allowing researchers to perform specific analyses or invasive sampling detrimental to the preservation of the fossil. On the other hand, scientists may find their analyses complicated by multiple factors including taphonomy, or restoration techniques (e.g., consolidants, cleaning chemicals). We provide several historical examples illustrating the complex nature of the factors acting on fossil preservation. We discuss concerns about producing and sharing (digital) data from fossils. Finally, we also suggest and support some curatorial practices which maximize the traceability of treatments underwent by a fossil.*

Keywords - *Conservation, Destructive sampling, Specimen history, Restoration practices, Physical and chemical alterations.*

Since the earliest discoveries of fossil hominin remains that attested the antiquity of man, about two centuries ago, a plethora of new fossils have been unearthed. Curators are delegated the tremendous task of maximizing the value of fossil remains by collecting information about the specimens and preserving as best as possible their physical and chemical integrity. In addition, they have to find the right balance between the needs of current research and those of preservation for future generations (Baars, 2010). Those decisions are complicated by the fact that the perceived scientific value of an artifact differs according to the background of the researchers. Therein lies the difficulty of defining the value of a fossil (Knell, 1991), as this comprises several components (Baars, 2010): historical (e.g., conditions of discovery, discoverer, history of science), scientific (e.g., for answering specific questions or for methodological aspects), potential for research (which helps the curator make an informed decision about allowing invasive sampling, for instance) and finally future importance (for as yet undeveloped techniques or fields of interest). This paper aims to further raise curator's and researcher's awareness of the importance and the need for keeping a detailed record of all procedures conducted, so as to trace potential

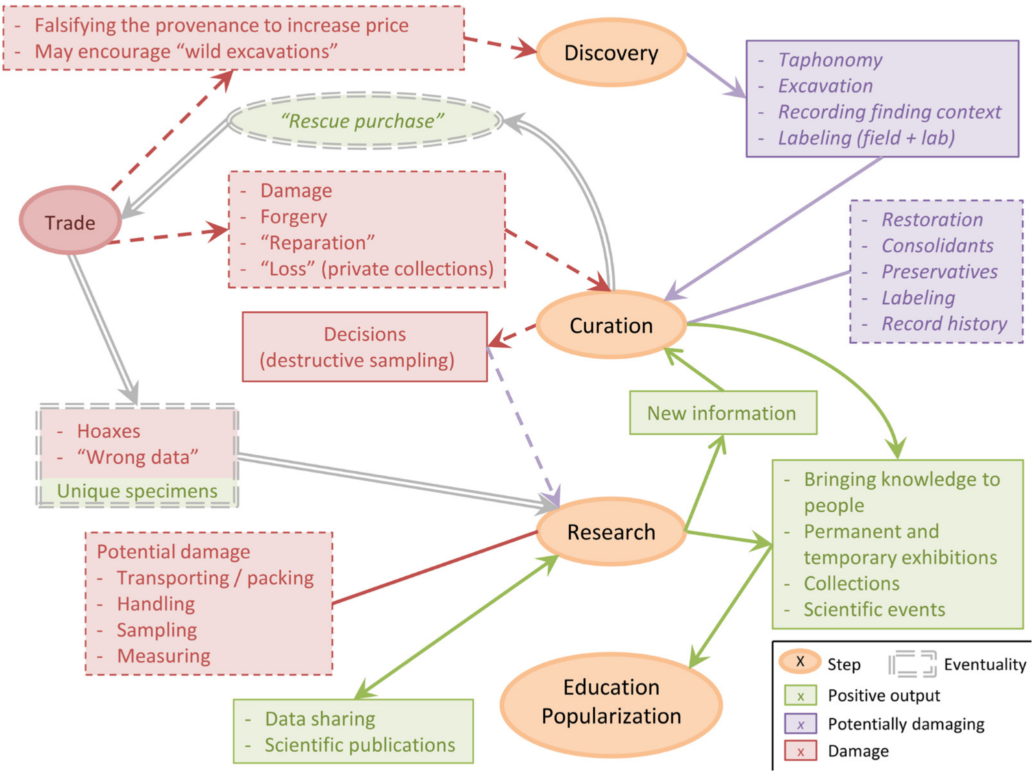

Fig. 1 - Flowchart showing the complex and entangled interactions between curation, restoration, research, and fossil trade. The potentially harmful interactions are listed in purple and italics (black font, medium gray-shaded in print); while the detrimental links are represented in red (dark gray-shaded in print) and the positive outputs in green (light gray-shaded in print). Double-lined arrows and frames show links which impact may not be systematic although significant when occurring. The colour version of this figure is available at the JASs website.

damage to a fossil: from excavation, to restoration, handling, measuring and sampling. These might indeed bias future analyses. This report is a reminder to all of us who manipulate remains from the past that they are unique and that it is our duty to ensure their preservation and availability for future generations.

The challenges of curating fossils

Conservation practices and sampling events can be sorted into four categories: (1) those inducing a loss of information about the specimen; (2) those having visible effects on the specimen (produced by physical and mechanical alterations), as for destructive sampling (e.g., ancient DNA [later abbreviated as aDNA], dating and isotope studies); (3) those interventions on the fossils having no macroscopic effects but other changes that are detectable by chemical analyses, which can thereby be biased or compromised (e.g., aDNA, ^{14}C); (4) those which may induce an aesthetic change in the specimen. We will discuss several detailed examples to support our recommendations and warnings. To assist the demonstration, we present a flowchart, which reveals how entangled and interdependent are all the factors and actors intervening around fossil remains (Fig. 1).

Detrimental loss of information

Major obstacles can compromise the value of a museum specimen. Vonica *et al.* (2011) recall that the main criteria for a researcher to judge of the scientific value of a fossil are the secured knowledge of its current name, its collection site and the conditions of discovery (e.g., stratigraphy, time of excavation), and its type status. The main points of concern are discussed in the following sections.

Archeological context

Loss of archeological context often results from old excavations: this is certainly the case for the Engis and Spy Neanderthal remains in Belgium (Toussaint *et al.*, 2011). Furthermore, the 19th century saw an increase in interest for collecting fossils as a leisure activity, and keeping the information associated with the fossils was not a priority in these old collections (Vonica *et al.*, 2011). Some specimens may also have suffered from negligence, because of their anatomical status (postcrania were less considered than cranial remains in former times), or because they were fragmentary and not the holotype. This brings us back to the question of the importance of a fossil: why should one be more careful with the holotype than with the other remains (Knell, 1991)? There are, although, good examples of former discoverers keeping a detailed description of context in their excavation notes, such as at the early hominin site of Ishango (Democratic Republic of Congo; Crevecoeur *et al.*, 2014). Aware of these concerns, modern excavations perform a meticulous and detailed work of information recording: e.g., Scladina (Belgium) since 1983 (Toussaint & Bonjean, 2014), El-Sidron (Spain; de la Rasilla Vives *et al.*, 2011) and Mezmaiskaya (Russia; Golovanova *et al.*, 1999). All types of information matter: although a specimen may have been overlooked because of its low potential in containing important morphological information, it could however be used for chemical analyses (e.g., aDNA). The knowledge of its context of discovery is then crucial regarding many aspects, such as its stratigraphic position, paleoenvironment, dating and association with tools or other bony or dental remains (Toussaint *et al.*, 2010).

A posteriori recovering of information: e.g., anatomy

The state of preservation of the remains can at first glance jeopardize its anatomical attribution and/or its morphological description, but *a posteriori* metric analyses or other quantitative investigations can sometimes shed light on this issue.

As an example, the anatomical attribution of the La Quina H21 (Q858, later abbreviated as LQ-H21) canine is a matter of debate as the tooth is worn and determining whether it is a mandibular or maxillary canine is not possible from visual inspection of the root alone. In his excavation notes in 1926, as well as in a later publication (Martin, 1927), Henri Martin described it as a left maxillary canine, as reported by C. Verna (2006a,b), who rather identifies it as a mandibular right canine (Verna, 2006a,b, 2012). We investigated whether root metrics could help decipher this anatomical issue. To do so, we used comparative samples of Neanderthal canines used in a previous study (Le Cabec *et al.*, 2013), to which we added two extra teeth: the lower right canine VI-11-39 (also called Vi 11.39 and Vi 206) from Vindija, and the upper right canine from Marillac (M71-C10 F12-93). The LQ-H21 canine (housed in the musée des Confluences, Lyon, France) was scanned on the BM05 beamline at the ESRF (Grenoble, France) by P. Tafforeau, at 6.36 µm. The tooth was segmented at 12.72 µm and measured in 3D following the protocol explained by Le Cabec *et al* (2013). Adjusted z-scores (Maureille *et al.*, 2001) were calculated for the crown and root variables (Tab. 1 and Fig. 2). LQ-H21 clearly plots close to the mean of the sample of Neanderthal mandibular canines, which confirms C. Verna's conclusion. Similarly, a reassessment of the Taddeo Cave teeth has recently led to adjustment of their taxonomic and anatomical attributions (Benazzi *et al.*, 2011).

Labelling

Another crucial issue concerns the naming of specimens (Fig. 1). The original labels and

Tab. 1 - Adjusted z-scores for the root length (RL), surface area (RSA) and volume (RV) and the labio-lingual crown diameter (Cr_LL) of LQ-H21 in comparison with samples of Neanderthal mandibular (LC) and maxillary (UC) canines. LQ-H21 classifies as a mandibular tooth (Azs values close to zero for the mandibular canines, i.e. the mean values of that sample).

		LC				UC			
	LQ-H21	**MEAN**	**SD**	**N**	**AZS§**	**MEAN**	**SD**	**N**	**AZS**
RL [mm]	**20.97**	20.63	2.88	17	***0.06***	22.37	2.43	13	*-4.25*
RSA [mm²]	**489.37**	408.61	95.32	17	***0.40***	449.16	60.62	13	*-3.43*
RV [mm³]	**583.97**	590.79	155.17	17	***-0.02***	643.25	98.34	13	*-3.03*
CR_LL [mm]	**9.42**	8.88	0.82	17	***0.31***	9.62	0.69	13	*-6.24*

§ Azs is calculated as: Azs = (x - m) / (TInv(α; n-1) * sd), with "x" the value of the specimen under investigation for the variable considered, "m", "n" and "sd" the mean, sample size and standard deviation of the reference sample to which the specimen is compared, "TInv" is the inverse of the Student's t-distribution; "α" was here chosen at 0.05.

names attributed to a fossil can be lost through time (Vonica *et al.*, 2011). The change over time of the name or accession number of a fossil can have dramatic consequences for keeping track of it in publications. Therefore, the inventory number should be consistently reported in publications to allow future generations to identify which specimen has been used, as well as which anatomical element has been sampled and when (for recovering the chronology of events). Barely readable handwriting or copies of labels made by non-specialists in museum collections will contribute to accumulating mistakes over time. This confusion related to specimen identification can also occur when there is refitting of several isolated parts (each with their own label) truly belonging to a single individual, or erroneously associated, such as in the Krapina collection (Wolpoff, 1979). Losing this information can lead to a tricky task of investigation in archives or in reasoning based on observation of the specimens in an attempt to recover the chronology of actions affecting its integrity. This is precisely how light has been shed on an erroneous reconstruction of the Kent Cavern maxilla KC4 and exposed the earlier misidentification of a permanent maxillary fourth premolar for a third premolar by former researchers (Higham *et al.*, 2011). Zipfel & Berger (2009) address these issues dealing with the labeling of fossils in the collections of the University of the Witwatersrand: demonstrating how different types of labeling can become confusing (e.g., "Sts" and "StW" for Sterkfontein) or even redundant, they propose a new labeling system designed to take into account all remains and record their site of origin and the fossil number so that the Taung child would be called "U.W.1-1".

Lost or sold?

More dramatically, the loss of the specimens themselves may be irreversible, such as for the Ksar Akil 1 juvenile remains which were lost on their way to Lebanon during repatriation (Bergman & Stringer, 1989; Tobias, 2005). In recent decades, many remains have been reclaimed by their land of origin. This is especially pertinent to the remains of Native American Indians, among which is the famous Kennewick man for which aDNA has permitted clarification of its debated population affinities (Rasmussen *et al.*, 2015). The sad case of the repatriation of the remains of Saartjie Baartman (also nicknamed as the "Hottentot Venus", who was even objectified during her life) from France to South Africa in 2002 involved a strong emotional and moral component, and this process was finally successful after years of negotiation between both governments (Qureshi, 2004; Tobias *et al.*, 2008).

A major problem lies in the fossil and human remains "business" (purchase and sale, sometimes illegally and/or in ethically disturbing circumstances; McCorristine, 2015) where specimens are lost to science or hidden in private collections (Fig. 1). Fossil collection and trade started as early as in the 18th century, with miners — and fossil-hunters — who were collecting specimens, preparing and selling them to museums or private collectors. These passionate gatherers developed new techniques of preparation and helped design new restoration materials, through their hard work in the field and in the laboratory (Larson, 2001). Purchasing fossils can be seen by some as an investment, comparable to buying a Picasso or another piece of fine art. Some remains may however reappear on the market one day (Kjærgaard, 2012). The 20th century has indeed seen growth in the occurrence of professional dealers and large international fossil fairs (Kjærgaard, 2012). The situation is complicated by the fact that laws, rules and habits differ from one country to another, and thus raises the question of the legality surrounding fossil trade in these international markets (Nudds, 2001). Private fossil collectors should strive for properly labelling fossils they gather and prepare, and record a maximum of information regarding the context of discovery, because without this, the fossil could lose an important aspect of its value (see above; Nudds, 2001). These private collectors could seek advice from professional curators (Rindsberg, 2005; MacFadden et al., 2016). Relating to the rarity of a fossil (as a gross caricature, e.g., a complete well-preserved hominin skull versus more frequently and numerously found cave bear teeth), an emotional and personal attachment will influence the value attributed to a fossil (the discoverer may develop the feeling that he owns the specimen; Tobias, 2005) as well as the price for which it could be sold. A falsified provenience can on the one hand serve inflating selling prices, but on the other hand jeopardize any future accurate scientific research (Fig. 1). Online advertising often does not allow professional paleontologists to verify for the authenticity of the remains, rapidly prompting caution regarding fraud or the putative scientific value of the item (Kjærgaard, 2012). Curators are faced with the dilemma of seeing (more or less) valuable or unique fossils escape from being hosted in public institutions via this (not always legal) market,

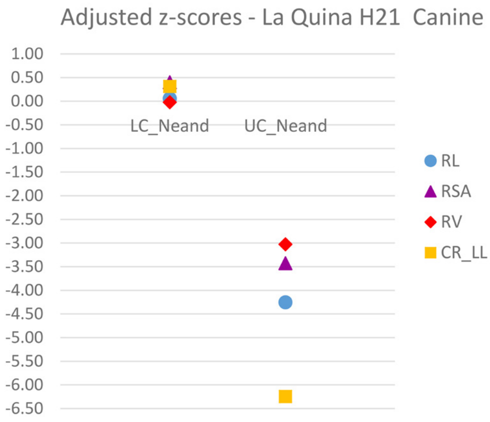

Fig. 2 - Plot of the adjusted z-scores (see Table 1) classifying LQ-H21 as a mandibular canine. The colour version of this figure is available at the JASs website.

and the ethical issue of taking part in this business (granted that they have the financial means to do so). Yet, a "rescue purchase" can contribute to preserve these remains for research and public access (Fig. 1; Nudds, 2001).

Some other circumstances can also result in the physical destruction of fossils, such as during armed conflicts. This is however less critical in nowadays more stable regions of the world than the fossil trade. The remains of Le Moustier 1 is a famous example of such a transaction, it was sold to a museum in Berlin during the 1910s. Subsequently during World War II (WWII), the museum was severely damaged during bombing and the fossil was thought to be lost, until some years later when several fragments were rediscovered (Maureille, 1997; Ponce De León & Zollikofer, 1999; Ullrich, 2005). Again during WWII, the remains of Peking Man (Mann & Monge, 1987; Berger *et al.*, 2012) were lost, although a thorough investigation has revealed traces of their displacement, and may grant future potential for unearthing them in China. Some isolated teeth had however been sent to Uppsala University before WWII, among which was a canine that has recently been rediscovered (Kundrát *et al.*, 2015). This case illustrates as well how remains can be spread over the globe

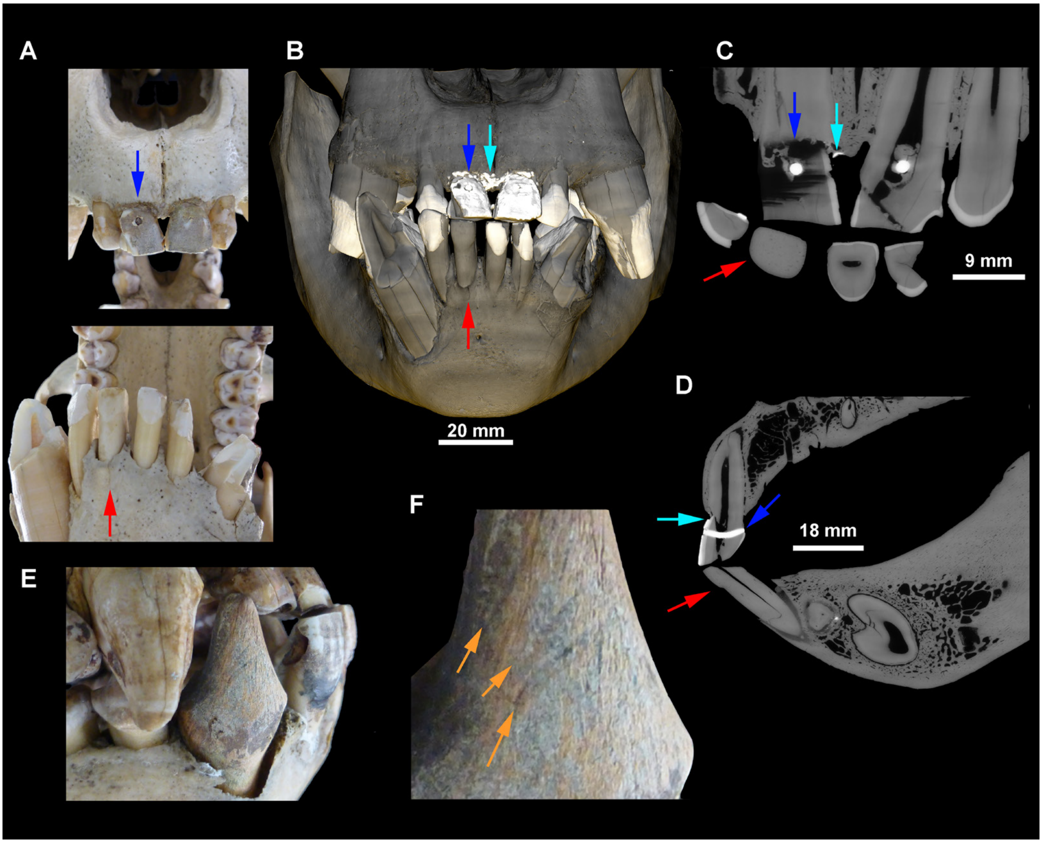

Fig. 3 - Examples of dental restoration in extant great apes (A-D: male* Gorilla *from Gabon, specimen ID: 50001972; E-F:* Pan*, specimen ID: 50001973) from the osteological collection housed in the musée des Confluences (Lyon, France). Photographs (A), 3D rendering (B) and 2D cross-sections in a synchrotron micro-CT scan (C, D; pixel size: 91.96 µm) of the* Gorilla *dentition showing an artificial right mandibular lateral incisor (red arrows) and the maxillary incisors in which coronally broken crowns are fixed with nails (blue arrows) and glue (turquoise arrows). Photograph of an artificial right mandibular canine made of wood (E-F) in the chimpanzee jaw. The colour version of this figure is available at the JASs website.

and over time. It was also during WWII that most of the Upper Paleolithic remains from Předmostí were destroyed as the museum which housed them was severely damaged (Mann & Monge, 1987). In contrast to the regrettable loss of the Peking Man remains — Weidenreich left the originals in China and brought the casts with him to the USA — the fossils from Java were "saved" by von Koenigswald who tricked the Japanese invaders by cleverly leaving very well-made plaster casts in Java and by exporting the originals to the USA (Tobias, 2005).

Unmasking hoaxes

Hoaxes can easily add confusion in this context. Fuzzy acquisition records can hinder the recognition of non-valuable elements. Forgeries, such as the famous Piltdown Man (Buck & Stringer, 2015; De Groote et al., 2016), are not always easily identified with the naked eye: scientists may initially trust their scientific integrity and honestly include them in their research (Fig. 1). They, however, can be confounded by meticulous investigations (Oakley & Weiner, 1955; Erdmann & Caldwell, 2000; Mateus *et al.*, 2008; Martins *et al.*,

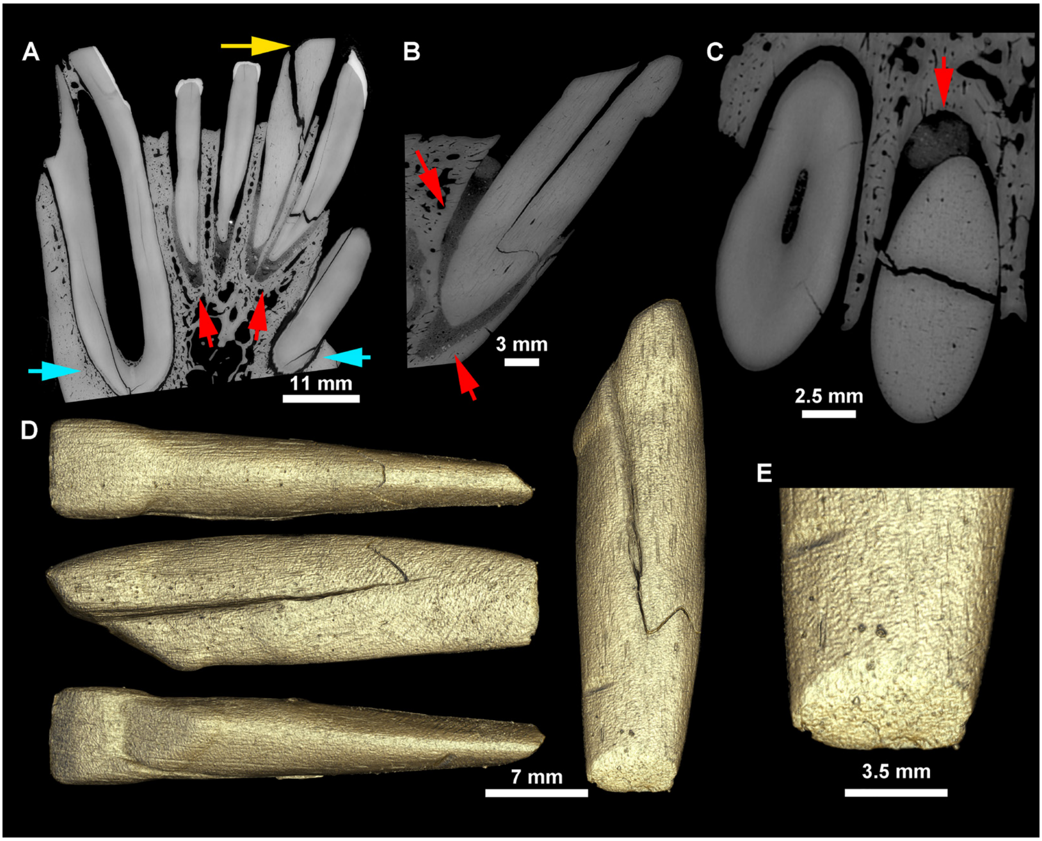

Fig. 4 - All incisors in the* Gorilla *mandible (from Fig. 1), including the artificial tooth (yellow arrow), have been glued back into the jaw (red arrows on A, B, C) while the canines still stand naturally* in situ *(turquoise arrows on A). A closer look at the artificial incisor (B-C; voxel size: 45.98 µm) reveals that it is made of one single material. A three-dimensional rendering of the fake tooth suggests that it was carved in bone, which may have later cracked due to desiccation (D, E). The colour version of this figure is available at the JASs website.

2011; Zipfel *et al.*, 2010) such as X-rays or UV fluorescence. Restoration of a specimen can involve making a replacement for a missing tooth for aesthetical purposes, even in modern collections. This is the case for some specimens housed in the musée des Confluences (Lyon, France), where a chimpanzee shows a wooden mandibular canine, and a gorilla a mandibular incisor made of a single material that is highly likely bone (Fig. 3). This latter case was detected during scanning acquisition at the ESRF, as this tooth was indeed made of a single material of lighter density than the dental tissues of the neighboring teeth and there was no pulp cavity. This status was later confirmed by closer observation (Fig. 4). A variety of materials have been used to make artificial teeth, among which are hippopotamus, elephant or walrus ivory, porcelain and bone (Cohen, 1959), or even human teeth coming for example from war casualties, such as in the case of the "Waterloo teeth" (Woodforde, 1968; Murray & Darvell, 1993).

Detecting intrusive elements

The loss of this primary information regarding discovery context can lead to finding intrusive elements or misidentification of human remains (Fig. 1). Therefore a careful labeling of isolated elements should include the site code, the individual identification number and if possible the anatomical element as precise as possible e.g., siding (Caffell *et al.*, 2001). The two isolated incisors stored with the Steinheim skull were found not to belong to this individual but to be modern human intrusions (Le Cabec *et al.*, 2013). Other specimens initially not recognized as human remains were stored with faunal material such as Cova del Gegant (Arsuaga *et al.*, 2011) and Scladina before 1983 (Pirson *et al.*, 2014) or stored with lithics or sediment lumps as for Le Moustier 2 (Maureille, 2002a,b).

Logging the specimen history

Recording all minor damage (e.g., enamel flakes on tooth or bone splinters) should become systematized: what is negligible today may gain importance in the future. One of the best examples concerns the precautions required during handling prior to aDNA analysis that have only been taken since the 1980s, when aDNA studies began (Baars, 2010). Especially for aDNA studies, ideally, records should be kept of all people handling or touching the fossil. Restoration and treatment practices should also be carefully recorded (Panagiaris, 2001; see below). While this was still a crucial issue less than a decade ago, recent methodological advances have permitted significant reduction in the risk of sequencing modern contaminations and improved the authentication of aDNA, especially by recognizing characteristic damage patterns in ancient biomolecules (Skoglund *et al.*, 2014; Knapp *et al.*, 2015; Renaud *et al.*, 2015).

Photographs taken over time would contribute to documenting the evolution of the specimen through time, for its external aspect (See the later described example of the Ehringsdorf G2 incisor). A digital record of the specimen history should be kept up-to-date: loans, to whom, what for, when (including return dates), restorations and damage. Global digital collection is beginning to be highly encouraged in paleoanthropology (Nigro *et al.*, 2003; Reed *et al.*, 2015). As digital media evolve rapidly over time, it may be useful to consider keeping a hand-written back-up (i.e., a logbook associated with each specimen). A further argument to keep a parallel handwritten log is that in several years' time some digital media may no longer be readable for technical reasons (incompatibility with current operating systems; readers do not exist anymore or can be seldom found, e.g., floppy disks), or due to physical alteration (the medium irreversibly deteriorated over time). A radio-frequency identification microchip could be implanted or affixed on each specimen for keeping track of identity and record history, but this would involve affixing this tiny element directly onto the specimen. To avoid any risk of damaging the specimen, the chip could be inserted directly in the box containing the fossil, but with the danger of losing the box or swapping boxes among specimens! In addition, and overall, this operation would represent a certain cost for large collections and structures which do not necessarily have the appropriate funding.

Physical/mechanical alterations

The physical integrity of a specimen can be irreversibly affected by various mechanical modifications.

Taphonomy and excavation

The primary factor of such alterations is taphonomy, manifestations of which include weathering, diagenesis, or abrasion (Grupe, 2007; Fernández-Jalvo & Andrews, 2016) which may leave non-negligible marks on the remains. This can, for example, later impact dental microwear studies (King *et al.*, 1999; Pérez-Pérez *et al.*, 2003). A thorough description of the taphonomy and a comprehensive understanding of the site formation process are crucial for later macro- and micro-morphological and biomolecular investigations of the bony and dental remains (Holland, 2016). This was, for instance, recently done for the Dinaledi Chamber in South Africa (Berger *et al.*, 2015; Dirks *et al.*, 2015).

Next, damage can occur during excavation (e.g., use of metallic tools) but also during post-recovery treatment: e.g., Scladina, Broken Hill, Tabun I, Skhul 4, La Quina 5 and Malarnaud (Fox & Pérez-Pérez, 1994; Bonjean *et al.*, 2014). One of the most extreme examples being when, in former times, fossils were recovered in caves opened by dynamite blasting, often for exploitation of limestone, such as, to cite a few sites, in Swartkraans (Brain, 1970), Taung (Tobias, 2006), and Sterkfontein (Clarke, 1998; Potze & Thackeray, 2010). This was the case for the discovery of 'Mrs Ples' *(Australopithecus africanus*; Potze & Thackeray, 2010) by R. Broom in 1946. To recover the skull of Sts 5, two blocks were prepared with a hammer and a chisel resulting in separating six blocks of breccia. Due to the technique of preparation, a thin layer of cranial bone stayed adherent to the breccia and was thus separated from the skull itself. This was revealed only 50 years later (Thackeray, 1997). Similarly, R. Dart exposed the skull of the Taung child from its surrounding matrix using a hammer, a chisel and a sharpened knitting needle borrowed from his wife (Tobias, 2006; McKee *et al.*, 2015). Later, Dart reports: "I was soon back in Johannesburg working away with hammer, chisels and knitting needle, in constant fear that the slightest slip of the chisel would shatter the relic within" (Dart & Craig, 1959, p. 10).

High-resolution casts can contribute (with the limitations discussed hereafter) to visualize the taphonomic marks left on bone surfaces (e.g., weathering, anthropic modifications, carnivore scores or chemical modifications related to the surrounding environment; Camarós *et al.*, 2016).

While metallic tools were systematically utilized in older excavations, these are still widely used today. Depending on the hardness and compactness of the sediment, but also on the a priori probability of finding faunal or human remains, wooden and plastic tools might be used instead (Tassie & Owens, 2010). Some present-day excavations however specifically use non-metallic tools, and report it in the publications, such as for the *Homo naledi* findings (Dirks *et al.*, 2015). In his review on the evolution of conservation techniques, Brown (2012) reports that, at the end of the 19th century, a treatment with hydrochloric acid was often/sometimes used to mask the damage occasioned on bones by preparation tools. This process would, however, obscure further the external bone morphology. To counter these risks of damage during excavation and preparation, medical-computed tomography has been tested against manual preparation of blocks of compacted sediment potentially containing faunal and human remains from Malapa (South Africa; Smilg & Berger, 2015). This virtual excavation technique proves to be reliable in guiding the manual preparation of fossil remains, although this may be prejudiced by the degree of fragmentation and the size of the bones, as well as the density of the surrounding matrix (which may induce scanning artifacts; Smilg & Berger, 2015). In addition, Laser Induced Breakdown Spectroscopy (LIBS) was recently tested to assist and control the laser removal of the surrounding matrix in fossils from Malapa and showed to cause negligible damage to the fossils (Roberts *et al.*, 2012).

Packing, handling and measurement tools

Transportation (Fox *et al.*, 2015) and handling (Mann & Monge, 1987) of fossils also considerably increase the risk of physical alteration (Fig. 1; Janaway *et al.*, 2001). The repetitive packing and unpacking of specimens with materials containing small porosities or asperities (e.g., foam) can have such consequences. For instance, in the case of a tooth packaged in a tube with pieces of foam, if there is a fissure or crack in the enamel, the foam can get caught in the tip of the crack and tear off a flake of enamel, even during very careful handling. Workshop sessions are even organized at conferences to train researchers and students and teach them how to avoid the most common mistakes in packing fossil specimens (Caffell *et al.*, 2001; Fox *et al.*, 2015). Additionally, bony and dental remains should always be transported in a solid (plastic or metal) box of appropriate size with proper wrapping to avoid movements and shocks inside the box. Indeed plastic bags (e.g., minigrips) alone will not protect delicate parts of the remains such as friable cortical bone or the thin walls of a developing tooth root. For information, the packing conditions for the rehousing of the Kennewick man (USA) have been extensively detailed and published (Trimble *et al.*, 2001).

With the persistent evolution of techniques of investigation, these remains are studied over and over again, often involving numerous handlings. This repetitive handling can damage the specimens, not only in collections used for research purposes but also in teaching collections, such as bone loss, loss of entire skeletal or dental elements, bone fractures, surface erosion, repaired breaks, or failed repairs (Caffell *et al.*, 2001). Researchers notice that the aspect of a fossil changes over time due to the accumulation of damage (Monge & Mann, 2005). Measurement tools can also imprint traces and marks the surface of bones and teeth. A famous case concerns the skull of the Neanderthal juvenile Engis 2, where marks were interpreted as proof of cannibalism (Russell & LeMort, 1986). This view was however challenged by White & Toth (1989), who identified these as marks left by sand-paper used during restoration, by moulding and by the use of a cephalic compass. Pencil marks or grooves may have been deliberately imprinted on remains for visualizing anatomical landmarks (Monge & Mann, 2005). Microscribe and caliper metallic tips can leave minute damage as well (Mann & Monge, 1987).

Restoration and consolidation

As just shown with the example of Engis 2, restoration and consolidation techniques can also result in detrimental physical alterations of the specimens (Fig. 1). This, however, depends on the time period when this restoration was performed.

One could cite the Neanderthal mandible BD1 (from La Chaise - Abri Bourgeois-Delaunay shelter, Charente, France) which was fixed with a metallic wire (visible in a micro-CT scan) and some material to replace the missing mental region. For many people, a specimen actually reaches a higher value when all parts are mounted back together in their natural position (e.g., rami, teeth) instead of leaving the isolated parts undamaged by any treatment for a remontage (Hill, 1886; Brown, 2012). This increased value is not only undeniable for educational and representational purposes, but also for some measurements and comparisons which would otherwise be difficult and inaccurate. However, nowadays virtual reconstructions should be preferred, as this can enable display of reconstructed replicas (3D prints at various scales, see hereafter) in exhibitions.

Another similar example concerns a metallic post that was inserted into the maxillary lateral incisor of the Ehringsdorf G2 juvenile (Vlček, 1993), after the pulp was drilled and the root tip fixed back with some material of restoration (details in the next section, Fig. 4). In addition to the fact that the internal morphology has been damaged by preparation practices, metallic inclusions will have a strong impact on the image quality of computed-tomographic scans. Mostly in former times, the preparation for restoration itself can involve other materials and techniques such as plaster, matches, polish, the use of a rebate plane and resins. At the end of the 19th century, Fraipont & Lohest (1887) restored and consolidated the skulls of Spy I and Spy II with plaster. Semal *et al.* (2005) report virtual cleaning of the cranial bone fragments from CT-scan data. This allowed for testing of the refitting of several extra bone fragments recovered during excavations in the 1950s. Likewise, Benazzi *et al.* (2011) have virtually corrected previous restorations on the Taddeo 1 and 2 teeth following a DNA sampling in the middle of the tooth roots.

Of the importance of publishing the nature of the restoration

The history of the reconstruction of the La Chapelle-aux-Saints skull is edifying, as reported by Heim (1989). In the early 1910s, Marcellin Boule undertook the reconstruction of the skull, with the limited knowledge of the neanderthal skull available at that time (Boule, 1911-1913). Therefore the manner in which the bones and fragments were assembled was strongly influenced by the preconceived idea he had about the place of Neanderthals in evolution (between an ape and modern man). This was motivated by the need to describe the specimen in a monograph and to take various measurements, which were nonetheless influenced by the reconstruction itself (Panagiaris, 2001). Fragments (e.g., basicranium and mid-face) were forced into contact or twisted, thus inducing a non-natural asymmetry; elements of the mid-face were also mistaken. Various materials were used to hold the fragments together, e.g., plaster, wax, cork, or even a metallic nail that was visible in old radiographs of the skull (Heim, 1989). Because of the many mistakes in the reconstruction and of the threatened physical cohesion of the skull due to the deterioration of the restoration materials, Heim undertook disassembly of the whole specimen and built a new reconstruction in 1984-1985, at the Musée de l'Homme (Heim, 1989). In spite of the intention of rescuing the specimen (using plastiline), this involved further manipulation and cleaning of some pieces.

Some interventions do not visibly affect the external physical aspect of the specimen, but X-rays can reveal an impact on the internal integrity of the fossil. This is the case for the permanent right maxillary central incisor Ehringsdorf G2 (1011/69) for which a metallic wire has been used to fix its root, which was broken in two after its discovery (Fig. 5). Vlčeck (1993) reports this observation, stating from H. Virchow's description of the tooth in 1920 (Virchow, 1920): "6.4. Reste des Kindes Ehringsdorf G – Vom Oberkiefer des Kindes sind isoliert der rechte I1/ und der linke I2/ vorhanden. H. Virchow betrachtete beide Schneidezaehne fuer gleichseitig. In Abweichung zur Abbildung bei H. VIRCHOW (1920) kam es spaeterer Zeit zum Abbrechen des ersten Incisivus und zur Fixierung mit Hilfe eines in die Pulpahoehle gelegten Drahtes." which translates as: "6.4. Remains of the Ehringsdorf G child – There are two isolated incisors from the child's upper jaw: the right central incisor and the left lateral incisor. H. Virchow interpreted the two incisors as belonging to the same side. In deviation from the pictures in H. VIRCHOW (1920), the central incisor was broken at a later time. It was fixed with a metallic wire placed in the pulp cavity." Although no information could be found in the literature, this fine work of restoration may have been performed by a dental practitioner (C. Dean, pers. comm.). This restoration work likely dates back to the 1960s. After the pulp was drilled, a post was inserted to fix the tooth, and silicate white dental filling material was likely used to restore the missing dentine and the external aspect of the tooth root (C. Dean, pers. comm.). This case highlights the importance of monographs containing detailed descriptions of the remains, as well as well-documented photographs and records of curatorial practices.

Casting and molding

Casting original fossils is crucial as the original specimens are not always made available for study, but also to protect the originals from repetitive handling, and for rendering them available for educational and scientific purposes for the larger community (Monge & Mann, 2005). This molding process is however not exempt of risk. First, casting/molding materials leave various chemical residues in dental fissures, foramina, cancellous bone, and between tooth and socket ridges (Fig. 6; Monge & Mann, 2005; Williams & Patterson, 2010; Bleuze, 2012; Camarós *et al.*, 2016). Second, there are non-negligible risks of damaging the original fossil, depending upon the material employed, the cast can be distorted or shrink over time, without the knowledge of the researcher. In addition, multiple molding sessions increase the risk of damage (Monge & Mann, 2005).

Destructive sampling

Hublin *et al.* (2008) have brought attention to the curatorial decisions and practices related to destructive sampling (Fig. 1), which is necessary for certain dating methods (such as ^{14}C), isotopic characterization and aDNA studies. The amount of material required for these analyses has however significantly decreased since the earliest studies, as technology improves such as in the case of laser ablation or accelerator mass spectrometry (Eggins *et al.*, 2003; Grün, 2006; Knoll, 2011; Lowe & Walker, 2015; Wood, 2015). This destructive sampling is justified at a time when no other non-destructive technique is available, as is the case for serial (micro-) sampling in

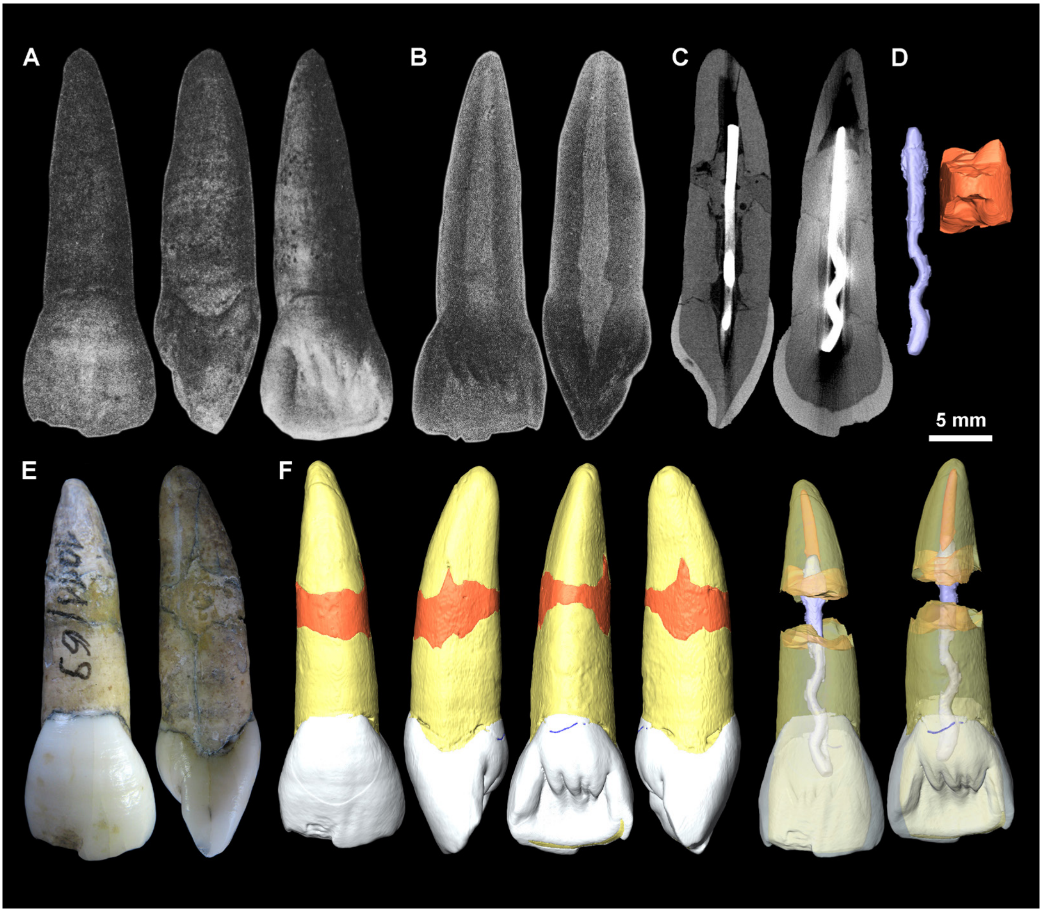

***Fig. 5** - Isolated maxillary right central incisor of the Ehringsdorf G2 child (1011/69). Original labial, distal and lingual photographs (A) and radiographs (B) taken by Virchow in 1920 (corresponding to his Tafel V – Figs. 6, 8, 9; and Tafel VII – Figs. 4, 5). Virtual 2D sections (micro-CT scans at 39 µm; C) in the tooth revealing the presence of a metallic post, the drilled pulp chamber and the restoration material, separately shown in 3D in D. Current photographs of the tooth (from MPI-EVA; E) and 3D models highlighting the external and internal restoration of the root (F). The colour version of this figure is available at the JASs website.*

isotopic studies (Fuller *et al.*, 2003; Eerkens *et al.*, 2011; Burt & Garvie-Lok, 2013; Fahy *et al.*, 2014; Julien *et al.*, 2015). While bulk sampling can leave pits of ~1 mm^3 (see Guiry *et al.*, 2016 for methodological investigations regarding sample spacing and depth), sequential laser ablation sampling produces much smaller pits (shots of ~0.3 mm of diameter and <1mm apart; Garcia *et al.*, 2015). Although gross morphology may be recovered by virtual CT-based reconstructions (Benazzi *et al.*, 2011), the internal and microstructural information formerly existing in the sampling area is definitively lost. During these kinds of sample preparation, involving partial destruction of the sample, the specimen can be totally destroyed by accident. This is unpredictable as it depends on *a priori* unknown parameters, such as concealed cracks in a tooth that under a certain amount of pressure will lose (for example during preparation of histological

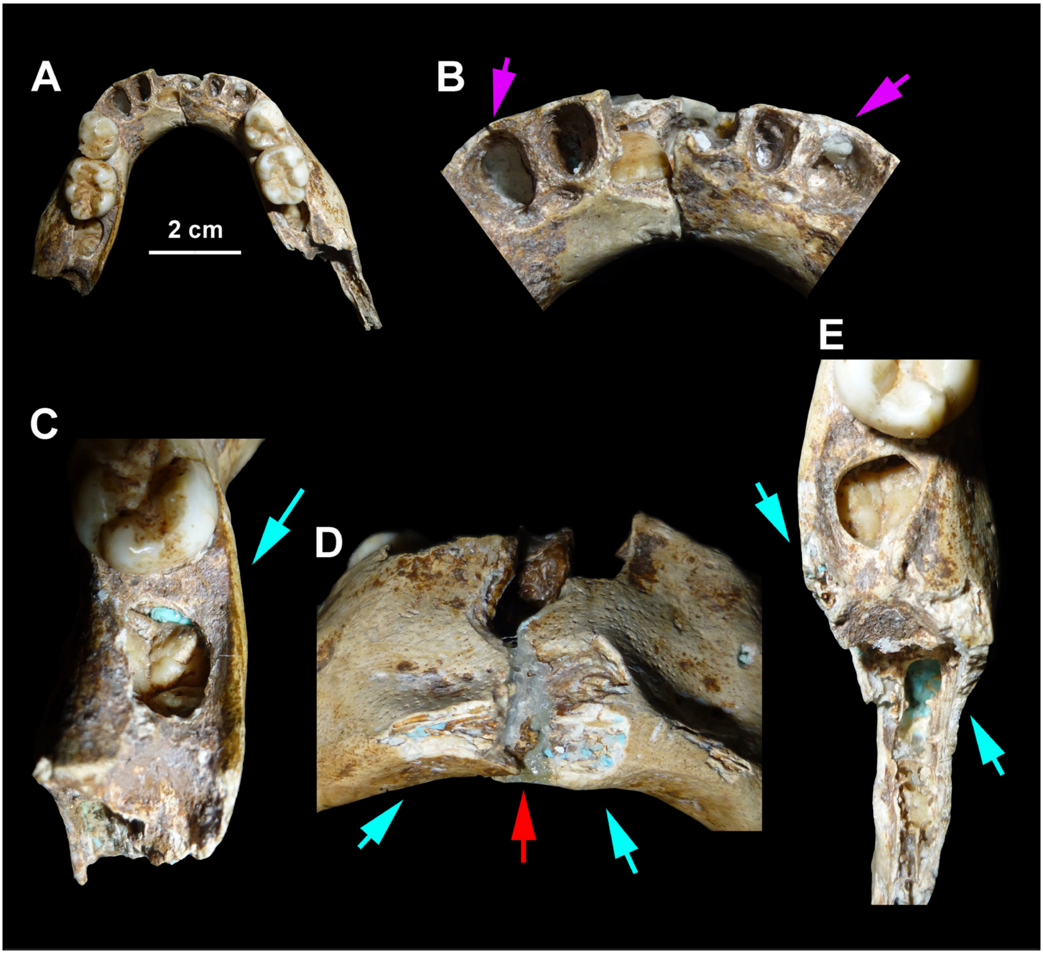

Fig. 6 - Photographs of the Badegoule 3 modern human juvenile (housed at the musée des Confluences, Lyon, France) showing the overview of the specimen (A), how probably casting material remains at the bottom of the bony sockets (B), and how casting material is incrusted in the crypts and cancellous bone (C-E). The broken symphysis has been glued (D, red arrow). The colour version of this figure is available at the JASs website.

sections). During ^{14}C dating, there may be risk of destruction for the most fragile teeth. The situation is however evolving regarding physical thin sections used for investigating dental development (such as for the Scladina tooth Scla A4-4; Smith *et al.*, 2007), as the on-going development of synchrotron imaging techniques and virtual paleohistology enables analysis without sectioning uniquely preserved fossils (Tafforeau *et al.*, 2006; Le Cabec *et al.*, 2015; Smith *et al.*, 2015).

Virtual back-up

Since its earliest development and use, computed-tomography (CT) has been regarded as a suitable non-destructive imaging technique for virtually backing-up/preserving fossils before destructive sampling or unpredictable damage occurs (Balzeau *et al.*, 2010; Hublin, 2013; Weber, 2015). This technique preserves both external and internal structure using digital media, whereas surface scanning offers a back-up of the external morphology (with possibility of texture recording; Friess, 2012). Faulwetter *et al.* (2013) explored the potential of micro-CT for creating virtual collections and “cybertypes”. The potential debates surrounding tomography imaging will be discussed in the next section.

Chemical alterations

Taphonomy

Not only can taphonomic processes induce mechanical damage but also chemical changes to the fossil (Grupe, 2007; Artioli, 2010; Brock *et al.*, 2010). Remains from a single site or even different parts within an individual can be differentially affected (Ovchinnikov *et al.*, 2001), as it is the case for the Scladina Neanderthal mandible for which the left part (Scla 4A-9) is more affected by manganese spots (MnO_2) than the right part (Scla 4A-1; Bonjean *et al.*, 2014). The understanding of diagenetic processes shaping the site should be taken into consideration whenever research on biomolecules is planned, such as for aDNA (Ovchinnikov *et al.*, 2001; Cooper *et al.*, 1997; Hofreiter *et al.*, 2012; Spigelman *et al.*, 2011). Although sampling is destructive, aDNA studies allow phylogenetic reconstructions to be addressed, recovering not only the timing of phylogenetic events and population dynamics but also the attribution of a specimen to genus, species and population (Hofreiter *et al.*, 2012). The next-generation-sequencing technologies give access to more aDNA and allow researchers to go further back in time (Hofreiter *et al.*, 2012). Whether collagen preservation can be used as a proxy for aDNA survival remains a matter of debate (Hofreiter *et al.*, 2012). Ancient proteins promise recovery of phylogenetic information from even earlier times than is reachable by investigating aDNA (Welker *et al.*, 2015). In addition to the risk of modern contaminations, these biomolecular analyses can be affected by molecular damage originating from taphonomy or from the chemicals used for preservation (Hofreiter *et al.*, 2012). Therefore, sampling for aDNA in situ, immediately following the unearthing of the remains would maximize the chances of recovering ancient biomolecules. Indeed these molecules would still be in conditions (mostly temperature and humidity) close to those in which they were preserved for thousands of years. Any post-excavation conditioning such as freezing may actually harm the integrity of these fragile molecules (Pruvost *et al.*, 2007). Bollongino *et al.* (2008) present a description of various sources of contaminations (e.g., tap water during washing) and damage, but more importantly they provide guidelines for optimized aDNA sampling, and encourage collaboration between archeologists and geneticists.

Consolidants and preservatives

The chemicals used in the post-discovery processes constitute, after taphonomy, the second major cause of chemical damage to specimens (Fig. 1). Cleaning the surface of a fossil with chemicals (e.g., acetone) can impact future analyses (López-Polín, 2012; Natali *et al.*, 2014), as this can lead to contamination by metallic compounds, and undesirable chemical elements. Unfortunately, there is no systematic record of chemicals used in the past, and the cleaning protocol remains at the discretion of the archeologist (Knoll, 2011; Brown, 2012). Any re-treatment may interact with previously applied chemical components and even further damage the fossil or compromise future studies (Brown, 2012). Publications reporting these technical actions on specimens remain scarce, although they would greatly help decision making prior to treating or sampling a specimen (Brown, 2012). For restoration or preservation purposes in museum collections, a specimen can be treated with pesticides, preservatives, glues or coatings which may all affect future biomolecular analyses, such as isotopic and trace element characterization or aDNA (Stephan, 2000; Nicholson *et al.*, 2002; Knoll, 2011). The packing material is also not negligible as some types of foam are acidic. Applied preservatives and consolidants, as well as harsh chemical treatment, can have dramatic effects on isotopic or radiocarbon analyses (Hedges & Van

Klinken, 1992; Takahashi *et al.*, 2002; Monge & Mann, 2005; Knoll, 2011; López-Polín, 2012). Johnson (2001) discusses the pros and cons of various materials used as consolidants, as well as providing guidelines for excavation and preparation techniques for minimizing the need to use chemical treatments.

The use of "hide glue" (animal origin, containing collagen from bone, tendons, skin, etc.) can be compensated for in isotopic analyses by a thorough dissolution of the glue coating the bones of interest. However, this extra source of modern collagen will disturb radiocarbon dating (Takahashi *et al.*, 2002). Ancient DNA research also suffers greatly from this: Sawyer *et al.* (2012) report the impact of the treatment of bones housed in museum collections with "ponal glue" (wood adhesive containing polyvinyl acetate) and "Leipzig Cocktail" (sulfuric acid-based preservative). They observe a purine overrepresentation in aDNA (Sawyer *et al.*, 2012). Varnish coating can also compromise analyses as reported by Russell and LeMort who failed to remove the shellack covering the Engis 2 skull in an attempt to use SEM to scrutinize the marks left on the cranial bones, so as to test their hypothesis of cannibalism (Russell & LeMort, 1986). Even more strikingly, the varnish covering the Engis 2 skull has led to two very different dates obtained from two different labs, by radiocarbon dating contiguous cranial fragments (Toussaint *et al.*, 2011).

An additional issue concerns the aging of consolidation/restoration materials. Indeed, their chemical and mechanical properties may change over time and their removal or dissolution may no longer be reversible (Howie, 1984; Nudds, 2001; López-Polín, 2012). Alternatively, the consolidating materials may fail to maintain the mechanical resistance of a restored specimen over time, as this was the case with the first reconstruction of the La Chapelle-aux-Saints skull described by Heim (1989) and reported earlier in the present study.

X-ray tomography

Concerns have been raised regarding the impact of X-rays (radiographs, medical CT, industrial and synchrotron μ-CT scans), as ionizing radiation could affect the retrieval of aDNA after scanning acquisitions (Richards *et al.*, 2012). Until very recently, all studies claiming that X-rays damage aDNA were lacking experimental data (Richards *et al.*, 2012) or relying on DNA extracted from modern or very recent specimens (Götherström *et al.*, 1995; Grieshaber *et al.*, 2008). Faulwetter *et al.* (2013) tested the effect of micro-CT scanning on polychaetes (specimens involving hydrated soft tissues) fixed in different media, and could not detect any degradation in the 16s rRNA sequences neither before nor after scanning. Current research is characterizing the damage to truly ancient DNA and delineating safe conditions for continuing CT-scanning (Immel *et al.*, 2016). A wise decision can be made to scan only half of the bones in the case of disarticulated bones of well-preserved specimens. This is what has been decided by Bruno Maureille regarding the paired elements of the Le Moustier 2 Neanderthal juvenile skeleton. Mirror-imaging will allow virtual recovery of the counterpart element, while the non-scanned element is preserved for future analyses (B. Maureille, pers. comm.).

Other issues concerning the use of synchrotron X-rays have been introduced regarding the color change occurring during X-ray acquisition of some dental remains (Horton *et al.*, 2010; Friess, 2012; Richards *et al.*, 2012). It has although been argued that most of the time exposure to daylight or if needed the use of UV light with the adequate wavelength usually allows recovery of the original aspect of the enamel (Tafforeau & Smith, 2008; Le Cabec *et al.*, 2015). The physical phenomenon behind this, the color-center effect, is discussed by Bertrand *et al.* (2012, 2015) in a review involving solutions to minimize the effect on transparent material such as dental tissues.

Finally, X-ray tomography can affect dating methods based on the quantification of radiation dose accumulated by materials, such as Optically Stimulated Luminescence (OSL) or Thermoluminescence (TL; Castaing & Zink, 2004; Artioli, 2010). Indeed, any radiograph will artificially increase the dose delivered to the object under investigation, and thus corrupt the result (Bertrand *et al.*, 2015). This would however concern mostly stony and ceramic materials, and much less bony and dental remains.

Neutron-tomography

Another imaging technique, neutron activation analysis (NAA), has subsequent impact on the chemical composition of a specimen, although it is much less widely used than X-rays. Depending upon the chemical composition of the specimen, some minerals, possibly acquired during fossilization (remineralization), can be activated during NAA and the specimen may remain radioactive for several years, preventing its access for future studies (Knoll, 2011; Martins *et al.*, 2011, 2015). Earlier attempts had been made to use neutron radiography to image the Sts 5 skull, after which the fossil returned to a background level of radioactivity (Le Roux *et al.*, 1997). Neutron-microtomography has however been recently employed to successfully image and distinguish the bony and dental tissues from the surrounding matrix of a fossilized skull from South Africa. While X-ray microtomography failed to yield a sufficient contrast to reveal the similarly dense materials, this imaging technique allowed a complete investigation of the specimen (Beaudet *et al.*, 2016).

Aesthetic changes

Although aesthetic changes have been referred to on various occasions in the previous sections, it needs to be underlined that the aesthetic aspect of a fossil may be affected in different ways after its recovery.

First, restoration can strongly affect the outer aspect of a specimen. Especially for those remains meant to be exhibited in museums: their aesthetic value is subject to special care, thus justifying a restoration. At first sight, a skull with a complete dentition would look much better in an exhibition than one with a partial or missing dentition (D. Berthet, pers. comm.). Thus the goal of restoration in this case would be to recover a presumed original (undamaged) aesthetic appearance. This is certainly what has led to the replacement of the missing teeth of the gorilla and chimpanzee in Fig. 2. Since these are great apes and thus subject to traffic, another possible goal would have been to maintain or even raise their selling price. However, nowadays restoration for museum collections tends to be more transparent, in that it serves the public understanding of the remains, although without misrepresenting what is preserved and what has been reconstructed. The restored regions are made clearly visible using a different color (D. Berthet, pers. comm.).

Some of these aesthetic restorations may affect scientific measurements, although it may also simply allow better visualization of structure, and decrease the risk of further damaging already fragile specimens.

Sampling events can affect the aesthetic of a specimen, especially in former times when the amount of material required for analysis was much larger than with present-day techniques. This may decrease the representational value of a specimen for display in a museum. As mentioned above, synchrotron scanning may induce a temporary change in color of dental enamel of certain specimens, although this is a reversible phenomenon (Tafforeau & Smith, 2008; Le Cabec *et al.*, 2015).

Thoughts for improving fossil preservation

Although some information lost from the past will never be recovered, the decisions it behooves curators to take to preserve specimens while promoting research are never straightforward. We would like to present some thoughts resulting from concrete experiences and propose some recommendations on how we should aim to manage fossil remains.

Recording research and curating history

A specimen will preserve its value if the maximum amount of information about its context and history has been recorded (Fig. 1). Curators should be encouraged to try to maximize sources of information regarding the history of the fossils in their care, such as damage and analyses. Especially regarding the fact that information may be lost from one generation of curators to another, in cases where there is very little or no transmission of notes from a curator to his/her successor. This approach should be completed by contacting even retired technicians, curators, or discoverers to maximize the retrieval of this important historical knowledge. In a larger context, regularly updating and populating an online catalog of fossils would contribute to centralize this historical and curatorial information. "*The catalogue of fossil hominids*" by Oakley *et al.* (1971), as well as its multiple revisions (e.g., Meiklejohn *et al.*, 2010) could serve as a basis, as it also provides information about repository for accessing the fossil itself or casts. Further descriptive categories could include "curatorial treatments" for reporting the use of chemicals or any substance likely to have a direct impact of future analyses. In the hosting institution, the specimen history should be regularly updated using digital media, and ideally with a hand-written back-up. This should include loans, to whom, for how long (including the date borrowed and the return date), any restoration treatment and damage. Regarding sampling and analyses, details should be recorded about which individual and anatomical part were sampled, ideally documented with photographs before and after sampling. The anatomical part should be clearly identified (as far as is possible) regarding anatomical element, side, accession number, location and date (for the chronology of events) of the sampling. In the best case scenario, a logbook (digital and/or hand-written) should follow the specimen over time, this is sadly not often the case (Seymour, 1988; Knoll, 2011; Brown, 2012). At the University of the Witwatersrand (South Africa), any researcher wishing to access the collections is required to complete an application form (B. Zipfel, pers. comm.; see *Info on the web*). This document contains the rules governing working with the collection, as well as a request to provide comprehensive contact details of the researcher, and to list the specimens for which access is requested, to document the purpose of the work, the techniques used (e.g., destructive), and whether any specific equipment would be brought to the collection. This application will be submitted to the approbation of an advisory panel at the University.

In addition, and to preserve their physical and chemical integrity, fossils should be stored in places with controlled temperature and hygrometry as inadequate conditions would accelerate decay and degradation processes (e.g., mold growth, development of fungi; Janaway *et al.*, 2001; Chareyron *et al.*, 2012). Physical security should also be considered (i.e., safes), as is very often the case in many museum collections and research institutions. The remains of the Scladina child are, for instance, stored in a room with controlled hygrometry and temperature. Each individual dental and bony element is conditioned in a small plastic box with a double membrane that holds the piece immobile; all the boxes are regrouped in a larger metallic case.

Protecting the potential for future studies

Upstream specimen preparation should take into account the requirements of planned studies, although it is always difficult to foresee in advance. In the case of aDNA studies, sampling should be performed directly from the site in strict sterile conditions: the excavator should be provided with the necessary clothing and equipment, in coordination with the geneticists (Fortea *et al.*, 2008). The curators should then ask to record all people handling/ touching the fossil, from excavation to the time where the specimen will be stored in a museum collection. There is however indeed a need for balance between the requirement for performing very sophisticated research and respecting curatorial practices as well as conditions that would otherwise significantly delay, complicate or raise the expenses for an excavation project. Namely, recent advances in detecting taphonomic damage to aDNA render less critical those factors which constrain sampling measures in the field (Renaud *et al.*, 2015). Similarly, portable micro-CT scanners can allow imaging fossils while avoiding the potential for damage during transportation.

Whenever the hardness of the sediment allows for it, excavation tools made of plastic and wood should be preferred in order to reduce the risk of damaging bony remains upon their discovery. In addition, photographs should be taken over time, on a relatively regular basis, to record the evolution of the specimen regarding its external aspect. Whenever using glue, consolidants or preservatives, casting materials or any chemicals, the curator should keep track of the material used (Fitzgerald, 1988; Monge & Mann, 2005; López-Polín, 2012). The precise chemical composition should be recorded, so that people who may want to perform chemical analyses on the fossils can be aware before sampling of the possible pre-existing limitations compromising the study.

Ideally, fragmented specimens should remain subjected to as little physical intervention as possible (although see below). For example, both Ms. Uta Olbrich-Schwarz (in charge of the osteological collection of the Taï chimpanzees at the Max Planck Institute for Evolutionary Anthropology, in Leipzig, Germany) and Mrs. Christine Feja (Curator of the human osteological collection of the University of Leipzig) recommend not using glue when a bone or a tooth is broken. They would instead rather safely store the tooth flakes or bone splinters in a bag clearly labeled, kept with the specimen (U. Olbrich-Schwarz and C. Feja, pers. comm.). As often as possible**,** specimens should be prepared as little as possible (López-Polín, 2012). This however depends on the state of preservation of the fossil, on the presence/absence and quality of preparation (see the La Chapelle-aux-Saints skull described by Heim, 1989). A minimal preparation is however desirable for some broken specimens, such as bone fragments which might be refitted over and over again by researchers so as to take measurements.

The decision to perform the restoration of missing parts of a fossil is left to the housing institution, and this is not mandatory (D. Berthet, pers. comm.). A specimen bound to stay in the storage rooms may not be subjected to as much restoration as another destined for standing in a showcase of an exhibition. This restoration would add to the value of a specimen for its presentation to the public, and facilitate its understanding by non-specialists (D. Berthet, pers. comm.). Nowadays, the restoration would mostly be accomplished in materials of distinct and lighter colors than the original specimen matter, so that it remains clear what was preserved and what has been prepared (D. Berthet, pers. comm.).

The question of allowing destructive sampling

The decision as to whether destructive sampling should be allowed is left to the curators (Fig. 1). This crucial responsibility covers the need for a balance between current research and preservation for the future (Baars, 2010). This choice is often a dilemma as the success of results is not always guaranteed, aside from the fact that the methodology often influences the results (Adler *et al.*, 2011): will there be enough contrast in the CT-scan of strongly remineralized bones/teeth? Will the collagen be preserved? Will aDNA be preserved or even exploitable? The careful study of the taphonomic context of a fossil find (e.g., pH, humidity) could efficiently guide the decision for sampling or not, as well as the choice of remains, and of the sampling location (Brock *et al.*, 2010; Hofreiter *et al.*, 2012). In *The catalogue of fossil hominids*, Oakley *et al.* (1971) report that analyses for relative dating were first performed on fossil hominid material, and that the results were compared when possible to those obtained from associated faunal remains. However, one should rather advise nowadays that if non-hominin material was unearthed in the same context as hominin remains, then sampling for biomolecular analyses or developing new techniques should preferably be attempted first on this faunal material. This was done for testing a novel and improved method for extracting ancient mtDNA in cave bear bones from Sima de Los Huesos (Dabney *et al.*, 2013). The thermal history of a specimen can greatly contribute to this decision as well (Ovchinnikov *et al.*, 2001; Smith *et al.*, 2001, 2003). Importantly, negative results should be reported as this could guide future investigation: as an example, the Scla 4A-4 molar tooth from Scladina that has not yielded aDNA despite two attempts several years apart, in two different labs (Bonjean *et al.*, 2014). The reasons why an analysis failed to yield successful results can be tricky to determine as all parameters (taphonomy, past chemical and mechanical treatments, or early stage of technology and methodology; Knoll, 2011; López-Polín, 2012) are entangled.

Curatorial decisions are made against a backdrop of constantly changing technologies and new developments, as well as new scientific and methodological challenges. Virtual histology (Tafforeau & Smith, 2008; Le Cabec *et al.*, 2015; Smith *et al.*, 2015) and the potential for retrieving aDNA in dental cementum (Adler *et al.*, 2011) constitute two good examples.

Virtual data and data sharing

The advent of (micro-)CT has allowed for new methods of conservation (Payne, 2013). Significantly, sharing digital CT data allows reduction in fossil handling and digitizing sessions. Open access to digital archives is also being promoted (Destro-Bisol *et al.*, 2014). Although this is not yet widely spread and tends, sometimes, to remain a pious wish, online databases provide free access to CT data of various fossil specimens (Friess, 2012; Hublin, 2013; Adams *et al.*, 2015; Weber, 2015; See the *Info on the Web* section).

The digitalization of fossil remains is far from solving all problems. As this was formerly the case for the fossils themselves (Tobias, 2005), the issue of ownership of digital data arises (Balzeau *et al.*, 2010; Zipfel & Carlson, 2013): would the owner be the museum? the institute that performed the CT acquisition? the researcher who has initiated the project? Or all of them? And then further questions come to light such as how to deal with data access. There can be signed agreements for restricted use, or embargos related to the use of the data by the researchers that initiated the project, at least until they have published their research (Tembe & Siddiqui, 2014). Over time, remembering special agreements may become tricky. Therefore and ideally, a folder associated with the CT data, as for any other kind of analyses, should include all the necessary information: who initiated the project and when, for what research project, who to contact to request permission to use the data (unless a signed contract specifies these conditions), who to acknowledge, what was scanned (maximizing details concerning specimen name, anatomical identification, dating, scanning parameters), associated publications, photographs and finally any notes or comments related to the data or the specimen.

Besides conditions for accessing data, indirect physical limitations could in fact restrict the efficiency of sharing digital data. As CT-scanning technologies evolve along with scientific analyses, and higher resolution and ever-improved image quality is required, the scientists willing to work with these large datasets may be limited by their computing facilities — requiring the cost of a basic license for the most commonly used 3D software (e.g., Amira or Avizo by FEI Visualization Sciences Group, and VGStudioMAX by Volume Graphics) reaching ~ 6.000 – 7.000 € —, the availability of sufficient data storage, and sometimes even limited by file format readability. Following these, the scientists need to possess specific skills for manipulating the CT-scan data and analyzing them according to their aims and research questions.

3D printing

Beyond their well-grounded interest for research, (micro)-CT scans involve the advantage of generating 3D prints of an object, at the natural size or at a different scale, and using different materials (e.g., transparent, colored). Depending on the specimen of interest, this is however not always desired by curators or project leaders. Nonetheless, this possibility has implications for educational purposes, as replicas used for teaching can be made available in potentially large numbers without risk of damage to the original fossil during handling (Tembe & Siddiqui, 2014). Finally, this allows access to fossils that remain in their country of origin (Tembe & Siddiqui, 2014).

Conclusion

Curatorial and research practices profoundly affect the conservation of fossil specimens and future analyses. It remains however a real dilemma to reach the right balance between forbidding any destructive sampling for the sake of specimen preservation and promoting progress in research with constantly evolving techniques. There is always a risk when allowing destructive analysis. For example, would one allow cutting a tooth for histological analysis or would one try to perform synchrotron tomography? And could the same level of information be reached? Would one sample the same specimen several years apart in an attempt to date it directly because of rapidly evolving techniques, with the detrimental effect being that the specimen is progressively vanishing? Research and researchers cannot however wait for all analyses to be done non-destructively with the highest level of precision, precisely because such progress is made by continued attempts. The curator should always be the guarantor and make informed decisions, and in this regard, the folder accompanying the remains is of primary importance.

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Info on the web

This list is by no means exhaustive, but only aims to help identification of online resources.

Online digital data sharing

http://www.isita-org.com/Anthro-Digit/data.htm
Anthro-Digit data repository — Data sharing from publication works.

http://www.australopithecus.org/datamine.html
Australopithecus.

https://carta.anthropogeny.org/museum/digital-anthropogeny
CARTA (Center for Academic Research & Training in Anthropogeny) — CT data.

http://www.virtual-anthropology.com/3d_data/3d-archive
Digital@rchive of Fossil Hominoids — EVAN; CDs and DVDs of CT and surface scans on sale.

http://www.sapalaeo.com/dnmnh-archive
The Ditsong National Museum of Natural History Plio-Pleistocene Palaeontology Section Digital Archive.

http://paleo.esrf.eu
ESRF paleontological microtomographic database - synchrotron micro-CT scan data.

http://morphosource.org/
MorphoSource - micro-CT and surface scan data.

http://paleo.eva.mpg.de/
MPI-EVA Human Evolution Microtomographic Archive - CT data, 3D pdf, movies.

https://www.nespos.org/display/openspace/Home
NESPOS - micro-CT scan data.

http://primo.nycep.org/
NYCEP Morphometrics Database.

http://plum.museum.upenn.edu/~orsa/Welcome.html
ORSA (Open Research Scan Archive).

Online catalogs and collections

http://humanorigins.si.edu/evidence/3d-collection
The Smithsonian National Museum of Natural History - 3D models.

http://www.pennfossilcasting.com/cart/agora.cgi
University of Pennsylvania Casting Program.

http://gbs.ur-plaza.osaka-cu.ac.jp/kaseki/
Catalogue of Fossil Hominids - Database.

https://www.wits.ac.za/microct/accessing-materials/
University of the Witwatersrand (Johannesburg, South Africa)

Conservation — online guidelines

https://www.si.edu/ResearchCenters/Museum-Conservation-Institute
The Smithsonian's Museum Conservation Institute.

https://www.flmnh.ufl.edu/vertpaleo/amateur-collector/preparation/
Florida Museum of Natural History.

http://preparation.paleo.amnh.org/39/conserving
American Museum of Natural History - PaleoPortal Fossil Preparation.

http://www.nhm.ac.uk/our-science/departments-and-staff/core-research-labs/conservation-centre/conservation-centre-training-consultancy.html
The Conservation Centre at the Natural History Museum of London.

http://www.unesco.org/new/en/culture/themes/museums/unescoicom-museum-studies-training-package/running-a-museum-a-practical-handbook
http://www.unesco.org/new/en/culture/themes/museums/unescoicom-museum-studies-training-package/running-a-museum-a-trainers-manual/#c163950
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