



# Weathering Stages of Proboscidean Bones: Relevance for Zooarchaeological Analysis

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## Abstract

This paper describes weathering modifications to elephant bones in Zimbabwe, southern Africa, and discusses possible implications about conditions of deposition and the time elapsed since death or skeletonization. The observed patterns of proboscidean bone weathering, the times elapsed since death, and burial times may not be same as for bones of smaller terrestrial mammals typically found in fossil assemblages. A system of weathering stages is proposed for proboscidean long bones, flat bones, mandibles, and ribs. Special attention is given to drying cracks that affect breakage patterns when weathered bones are trampled or impacted. Weathering effects on elephant bones vary for several reasons, such as differences between juvenile and adult cortical bone and frequency of wet/dry cycling. Also briefly discussed are the observed or possible effects of burning, dissolution, organic erosion such as root etching, and inorganic carbonate (calcite) encrustation. Comparable weathering effects are also reported on bones of *Mammuthus* spp., supporting the probability that (1) bone weathering in fossil proboscidean assemblages can be described in corresponding terms, and (2) implications about assemblage origins may be similar, although this inference must be cautiously drawn. The data reported here will allow analysts to describe assemblage materials in consistent terms.

**Keywords** Taphonomy · Zooarchaeology · Fossil assemblage origins · Bone exposure times

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## Introduction

Analysis of bone weathering is an important part of the study of fossil faunal assemblages. The term weathering refers to the effects of any “physical and chemical agents operating on ... bone in situ, either on the [ground] surface or within the soil zone” (Behrensmeyer, 1978: 153). Weathering data can aid in reconstructing local micro-environments of deposition and original conditions of bone preservation in fossil and recent bone assemblages, although the pathways of reasoning towards these interpretations are not simple (Gifford-Gonzalez, 2018; Lyman & Fox, 1989).

Many large fossil proboscidean assemblages were created in open-air settings. Weathering is known to be a major process that alters bone surfaces in open-air Paleolithic faunal assemblages, often making it impossible to identify traces of hominin actions such as butchering marks. Bone weathering was probably the main factor accounting for the scarcity of anthropogenic marks and breaks on bones which were associated with lithic materials that could have been butchering tools in several Lower Paleolithic open-air sites in Spain and Italy (Pineda & Saladié, 2022). The extent of weathering of bones from proboscideans and smaller animals in open-air assemblages may be perceived as different, as reported for the Middle Pleistocene site Torralba (Spain) (Pineda & Saladié, 2019), possibly because the bones were deposited at different times in the same spots, but also possibly because bones of very large animals weather differently.

Proboscidean bones with their very thick cortical layers, dense trabeculae, and large sizes may survive the attritional effects of weathering longer than the bones of smaller animals, thus affecting %MAU of different size animals in cumulative open-air faunal assemblages (*e.g.*, Pineda & Saladié, 2022). In addition, the patterns of proboscidean bone weathering may not be the same as observed for bones of smaller terrestrial mammals found in fossil assemblages, complicating the ability to estimate exposure time before burial and preservation. We think that a greater understanding of proboscidean bone weathering is warranted as a potential tool in taphonomic analysis.

Recent studies of African elephant skeletons (*e.g.*, Coe, 1978; Haynes, 1991, 2018; White & Diedrich, 2012) have focused on open-air localities. In this paper, we describe weathering effects on African elephant bones from open-air settings in Zimbabwe.

Numerous local variables are known to affect the weathering of bones from different sized animals in diverse environments (Andrews, 1990; Fiorillo, 1995; Andrews & Armour-Chelu, 1998; Andrews & Cook, 1985; Andrews & Whybrow, 2005; Haynes, 1981, 2018; Fosse et al., 2004; Conard et al., 2008; Gifford, 1981; Lyman and Fox, 1989; Tappen, 1994). Behrensmeyer (1978; Behrensmeyer and Faith, 2006; Behrensmeyer & Miller, 2012) published influential descriptive studies of bone weathering in mosaic habitats of southern Kenya, east Africa. Other actualistic observations of animal bone weathering have been made in central African rain forests (Tappen, 1994), temperate Welsh moorland (Andrews & Armour-Chelu, 1998), hyperarid Mid-East deserts (Andrews & Whybrow, 2005; Pokines & Ames, 2015), and North American mountains, temperate prairie (Fiorillo, 1989, 1995),

and boreal forest (Miller, 2009, 2011). As suggested by these and other studies, terrestrial mammalian bones in different global regions deteriorate at different rates although they are thought to have similar characteristics as they pass through progressive stages of deterioration. Proboscidean weathering has not been studied in detail to confirm whether the largest and densest bones follow the same patterns. Observational studies of human bone weathering in various environments also have been made, allowing forensic anthropologists to estimate the time between an individual's death and the discovery of skeletal remains — the *postmortem interval* — which may strengthen interpretations of the causes of human death (e.g., Pokines, 2016; Junod & Pokines, 2014).

Haynes et al. (2021) briefly described elephant bone weathering in southern African woodland and savanna, but the present paper offers more details and discussion of the patterned weathering of elephant bones, and also cites similar examples of mammoth bone weathering. A separate paper (Haynes, 2020) describes weathering of elephant tusks in southern Africa.

Our records support the application of a system of weathering stages to the Zimbabwe elephant bones, organized along the lines of the system Behrensmeyer (1978) devised after long-term recording of animal bones in the Amboseli Basin of Kenya. The weathering stages proposed here specifically pertain to the very large elements of proboscidean skeletons. We offer details about each stage, including estimates of variations in time-since-death as affected by local conditions. We also demonstrate identical modifications to fossil proboscidean bones from a variety of Eurasian and North American assemblages.

The bones of extinct *Mammuthus*, *Mammut*, and *Paleoloxodon* are similar in shape and size to those of *Loxodonta*, and a uniformitarian principle accepted here is that if there are similar weathering effects on comparable fossil and recent bones, they were created by similar or identical processes and agents in the past and present. The shape and size differences among the extinct and extant taxa possibly do affect bone-modifying processes to a degree, but our examinations of fossil collections indicate that weathering modifications correspond closely between mammoth and African elephant bones, and we suggest further research will document correspondences with bones of other proboscidean taxa.

## Materials and Methods

The information reported here was recorded in savanna, woodland, grassland, and bush/scrubland environments in the southernmost Tropics (longitude ~26° S) of Africa, in northwestern Zimbabwe. The climate zone of the Zimbabwe study region is classified as BSh or arid steppe hot climate in the updated Köppen-Geiger climate classification system (Kottek et al., 2006), although the elevation of this paper's study areas (average > 1000 m asl) moderates the climate so that conditions are more subtropical than tropical. Over half the year (April to October) sees mostly sunny and dry days with average daytime temperatures ~20–35 °C and nighttime temperatures ~7 to 3 °C. Freezing temperatures are possible at ground level. In

the wet season, daytime temperatures average 18 to 25 °C. Annual rainfall averages 400–600 mm p.a.

Actualistic fieldwork was carried out by Haynes for one or more months annually from 1983 to 2013. Most time in the field was spent in foot surveys searching for elephant bone sites. Over 1000 elephant death sites were examined, 814 of which Haynes had documented at the time the elephants died. Of that total, 402 had died of starvation in drought years and the rest had been shot in government-sanctioned attempts to reduce the elephant population in three conservation areas of north-western Zimbabwe (Hwange National Park, Zambezi National Park, Chirisa Safari Area). Dozens of other bone sites had been recorded by other workers, including five that dated back > 30 years. When bones were photographed or collected, the time-since-death was noted for all specimens in sites with documented death dates. The time-since-skeletonization was also recorded, if known. This is the length of time for skin, muscles, ligaments, tendons, periosteum, and cartilage to be naturally lost from > 50% of a bone surface. Lyman and Fox (1989:300) refer to this defined time span as *exposure duration*. The maximum length of time-since-death or exposure of bones in the sample was > 30 years; the minimum length of time-since-death/exposure was 1 week.

Some elements of the skeleton were not always present in the examined skeletal sites with known dates of death. For example, mandibles were missing from most sites because they were regularly collected for analysis by National Park personnel, except in 10 cases where overlooked carcasses or skeletons were found by Haynes. Dates of these deaths were estimated with confidence or were known from official records of elephants killed when seen to be injured; death dates were 10 days to 15 years prior to encounter in the field. During the natural process of skeletonization, the smaller elements such as carpals, tarsals, metapodials, and phalanges were partially or completely removed from bone scatters by scavengers or were scattered and buried by animal trampling, making it impossible to record progressive weathering characteristics in a rapidly shrinking sample. Cranial weathering also could not be rigorously recorded for several reasons: skulls in all but a very few skeletal sites had been damaged by chopping to remove rooted tusks; cranial bones of juvenile or young adult elephants had not yet fused at the time of death and as they dried they came apart and were frequently scattered or damaged by trampling; and adult elephants often removed large bones such as crania from skeletal clusters that had known dates of death.

At each visit or revisit to a bone site, Haynes made notes, took photographs, and occasionally collected bones. As many sites as could be found were revisited from 10 days to one or more years apart at least twice during the three decades of fieldwork. Over 300 skeletal sites were within grassy depressions and ~ 100 were immersed in temporary rainwater pools for a few hours to several weeks or months in some years. Differences in weathering rates were noted for the bones that were temporarily in water, but the progression of general weathering characteristics over time was not noticeably different from the sequential weathering of bones which were never in water, as described below.

A few buried skeletal clusters were excavated after being encountered in exploratory test pits. They had been naturally buried by animal trampling or

well-digging by elephants in silt, sandy silt, and sand, some time after their deaths were recorded (Haynes, 1991). A small number of very weathered bones from deaths recorded by other field workers > 15 years prior to Haynes's field study were also excavated, but it was impossible to tell if they had been subaerially exposed for any length of time before burial.

We demonstrate that this elephant-bone study is applicable in fossil analyses by illustrating a sample of *Mammuthus* bones with identical characteristics. These were examined in international facilities which curate large collections of fossil bones, listed in acknowledgements. During each visit and revisit to the collections, extensive notes were written and photographs were taken of specimens which showed effects similar to elephant-bone weathering or other modifying processes in nature. The purpose in examining the material was specifically to explore if our data can be used when describing particular fossil elements.

## Results

Even though the rates of weathering were observed to vary from habitat to habitat in some but not all years of the field study, the field records indicate that the *progression* of deterioration did not noticeably vary for subsets of long bones, ribs, scapulae, innominates, and mandibles. Statistical analyses relating rate of weathering to time since death in each habitat were not done, because local environmental variables within each habitat such as rainfall totals or vegetative coverage differed from year to year, sometimes significantly (50% or more for rainfall). In some years of the 30-year study, a habitat that was relatively dry such as bushland on sandy substrates might be wetter than the typically wetter habitats such as grasslands with depressions that filled with rainwater in other years. A comparison of weathering rates among habitats was not possible during different phases of the field study because of significant interannual variability in bone visibility, degree of shading by vegetation, and input of carcasses to the samples. As well, the numbers of each element visible to examine decreased in some habitats as the bones became buried or impossible to re-locate over the 30 year-long study. Another factor that discouraged analyses of habitat differences in weathering rates was the punctuated addition of large numbers of elephant deaths that were minimally scavenged by carnivores in drought years; the carcass skins would have dried hard and mummified the remains, delaying bone exposure, followed a few months later by recurring wetting in typically heavy rains and then rapid drying in bright clear sunshine. Haynes was not present in the study areas to record whether the wetting and drying affected bones equally in all habitats. Another factor was the punctuated additions of deaths from culling to reduce elephant population size; the culled elephants were immediately butchered in grassland, bushland, and open woodland, directly exposing bones from the skinned and meat-stripped carcasses to weathering, in contrast to the often mummified remains from drought-caused starvation deaths in the same kinds of habitats where bones were not exposed to weathering for months or longer. The starting conditions for bone exposure and weathering often differed significantly within and between habitats.

## Weathering Effects Can Be Classified into Stages

Behrensmeyer (1978) published a widely used system of stages for classifying the extent of bone weathering and discussed implications for interpreting the span of time involved in the creation of bone assemblages. Behrensmeyer (1978) divided bone weathering into six stages, 0 (unweathered) and 1–5. Behrensmeyer pointed out that weathering characteristics were not significantly different for bones in the different habitats of her east African study area, which is also what was found in this Zimbabwe study. Behrensmeyer noted that weathering studies in different environments on several continents show that “textural characteristics of the different stages [of weathering] are generally recognizable,” implying that structural features of bones may have “a major influence in the weathering characteristics regardless of external [environmental] conditions” (Behrensmeyer, 1978: 161). These studies did not focus on elephant bones for the most part. Behrensmeyer found that weathering rates in her study were slower specifically for bones deposited in swamps or dense woodland. No Zimbabwe elephant bones were deposited in these types of habitats, although localized conditions such as ephemeral shallow flooding in any of the habitats during the annual rain season did temporarily retard weathering of elephant bones lying in pools or wet patches; however, once the immersed bones were re-exposed, they progressed through the same stages of weathering as bones that had never been in water. Burial by natural processes also slowed weathering, but systematic long-term study could not be done because buried bones were hard to find. Elements which had been naturally buried by trampling or well-digging by elephants very soon after death showed no visible signs of weathering when they were discovered 2–5 years after death in test-pit excavations, as mentioned above, while bones which had weathered for 2–5 years before natural burial showed the same weathering effects recorded on them before they were buried.

Modern-day proboscidean elements deteriorate in phases as do the bones of smaller taxa. As with other taxa, weathering effects vary for different proboscidean elements. Some elements in the elephant skeleton show unique effects of weathering, as also recorded for other vertebrate taxa (Behrensmeyer, 1978; Lyman & Fox, 1989). Juvenile elephant bones weather faster than adult bones, as also noted for mammoth (Todd & Frison, 1986: 40) and extant nonproboscidean taxa (e.g., Behrensmeyer, 1978). One possible reason for the difference may be that juvenile and young adult proboscidean compact bone is made up of fibrolamellar tissue, a fast-growing material with highly vascularized woven bone, while the cortical parts of bones from older individuals are made up of tissue that is parallel-fibered and slow-growing (*i.e.*, still able to remodel). Another source of variability in bone weathering is the positioning of bones on ground surfaces. Bones that lay undisturbed in different biomes show differences in weathering of upward and downward sides (Haynes et al., 2021; Sutcliffe, 1990: 178, 179 Fig. 5; Tappen, 1994; Todd & Frison, 1986: 39 Fig. 2.5). Other sources of variability are time of exposure, intensity of ultraviolet light, and fluctuations in temperature and moisture; these have diverse effects on bones with different textures and surface areas (Behrensmeyer, 1978). Lyman and Fox (1989) suggested that variability in bone surface-area-to-volume ratios would result in discrepant weathering stages for elements exposed for similar time spans.

Elephant bone deterioration is a continuum, but for convenience, the process is here described in steps or weathering stages defined by specific features, as in Behrensmeyer (1978). Table 1 provides the weathering stage (WS) designations and criteria for assignment to each stage; Figs. 1, 2, 3, 4, 5, 6, 7, and 8 illustrate the important features. Stages are assignable when most bone surface of at least one major aspect (caudal, lateral, etc.) has the listed characteristics. The stage characteristics of ribs and flat bones (scapulae and innominates) differ somewhat from those of tubular bones. Also note that the definition of each WS may differ for adult and juvenile elements.

This structured way of classifying is practical but it cannot eliminate idiosyncratic interpretations. Vietti (2016) suggested that surface texture analysis (a measure of average roughness) using 3D scans can *quantitatively* characterize bone weathering and eliminate inter-observer disagreements in qualitative descriptions. A 3D scanning method was not available in the field, so the system proposed here is qualitative. The listed weathering characteristics of *L. africana* bones (Table 1) include an intermediate weathering stage (WS) for bones progressing between stages 0 and 1 and another intermediate WS for bones weathering between stages 1 and 2, because these transitions seemed the least clear-cut for assigning to a single determinate stage. Fiorillo (1989) also found that bones appeared to be transitioning between formally definable stages and were not always easily assignable to specific stages, as reflected in his Fig. 3 (Fiorillo, 1989: 63). Table 2 shows estimates of times since death/exposure of bones from proboscideans and nonproboscideans in different environments. Note the similarities and differences.

Dissolution and burning/heating also alter elephant bone surfaces, and some effects are similar to weathering. These are briefly discussed below in the “[Heating/Charring](#)” section. Other natural agents such as termites and tenebrionid beetles alter surfaces of large mammal bones but the effects are generally distinguishable from weathering (see, e.g., Fernández-Jalvo & Andrews, 2016; Haynes & Hutson, 2020; Keiler et al., 2020).

## Drying Cracks and Bone Surface Changes

Proboscidean bones develop linear or curvilinear cracks when they dry during exposure after death, as also recorded for other vertebrate taxa (Brain, 1981: 141). Drying cracks mainly reflect the orientation of collagen fibril bundles (Tappin, 1969). The orientation of collagen fibril bundles on long bones can directly affect fracture propagation when bones are fragmented by trampling or impact. Traumatic fracturing of long bones also creates cracks. Figure 9a and b show an elephant distal femur with a helical fracture outline, a smooth cortical surface, remnant soft tissue on the epiphysis, and two lengthy cracks that were created by the traumatic fracturing in life. Figure 9c shows a carnivore-gnawed elephant femur with marrow oil still present and a long and a short crack originating at the gnawed distal end, created by the gnawing carnivore and widened by drying. The bone in Fig. 9a and b was in WS 0 when collected in the field, and it later developed a fine hairline crack between the two trauma-made cracks as it continued to

**Table 1** Weathering characteristics of elephant bones in Zimbabwe and general characteristics described by Behrensmeier (1978) for bones in the Amboseli Basin of Kenya

Weathering stage (WS)	Characteristics of large long bones of Zimbabwe elephants	Characteristics of ribs/flat bones of Zimbabwe elephants	Characteristics of Amboseli Basin animal bones (Behrensmeier, 1978:151)
0	Smooth surface on compact bone with no drying cracks; soft tissue may be present or absent; marrow oil oozes out of diaphysis and epiphyses, eventually may disappear (Figs. 1 and 2)	Similar to long bones (Fig. 6a); ribs/flat bones may ooze marrow oil at epiphyses	No cracking or flaking is present or bone surfaces; bone is usually greasy, soft tissue may be present on some or all of the bone surface
0–1	Greasiness is mostly/all gone from diaphysis, may be present on epiphyses; incipient (fine) drying cracks appear on compact bone (Fig. 3a)	Similar to long bones; on adult and juvenile ribs, microcracks are discontinuous	[Not separately described]
1	Drying cracks are more visible on diaphysis (Fig. 3b and c); marrow is shrunken/dried inside the bone; patchy soft tissue may be present	Cracks are more open on ribs (Fig. 6b), not always linear on flat bones (Fig. 7a); surfaces are becoming rough on juvenile elements	Cracks are present, parallel to the longitudinal fiber structure on long bones; mosaic cracking is present on articular surfaces; soft tissue may or may not be present
1–2	Drying cracks are wider and longer, and crack edges are angular/sharp; cortical surface is no longer uniformly smooth; most marrow is gone; remnant patches of cartilage/soft tissue are possible; on juvenile elements, drying cracks may be obscured by exfoliating cortical layers	Similar to long bones	[Not separately described]
2	On adult elements, drying cracks are wider and longer, and not all crack edges are angular/sharp; cortical surface is roughening; patchy exfoliation ("flaking") is present; no cartilage/soft tissue is present (Fig. 4a); on juvenile elements, cracks may not be visible but surface is rough and exfoliating (Fig. 4b)	Juvenile flat bones have peeling outer cortical layers (Fig. 7b); adult flat bones have open and usually curved drying cracks, rough surface, patchy exfoliation (Figs. 7c and d); juvenile ribs have numerous discontinuous cracks creating a rough surface (Fig. 8a)	Outermost bone layers show flaking; crack edges are angular; soft tissue remnants may be present



**Table 1** (continued)

Weathering stage (WS)	Characteristics of large long bones of Zimbabwe elephants	Characteristics of ribs/flat bones of Zimbabwe elephants	Characteristics of Amboseli Basin animal bones (Behrensmeyer, 1978:151)
3	On adult elements, cracks are more open with rounded or rounding edges; larger patches of the cortical surfaces are peeling (Fig. 4c), exposing fibrous inner cortical bone; on juvenile elements cortical layers are peeling off in large patches (Fig. 4d)	Adult flat bones have open cracks with rounded edges and spalling surface; adult ribs have very rough surfaces with peeling splinter-like spalls (Fig. 8b)	Compact bone surfaces have rough and fibrous patches; gradually entire surfaces become rough as external concentric bone layers are removed; crack edges are usually rounded
4	Drying cracks are deep, exposing trabeculae; cortical surfaces are very splintery and fibrous; flaky laminar bone is peeling/spalling and increasingly fragile on adult and juvenile elements (Fig. 5a)	Surfaces fragile and exfoliating	Bone surfaces are coarsely fibrous, and small splinters may fall away; weathering has penetrated into the interior of elements; cracks are open and have splintering or rounded edges
5	Long fibrous splinters and spalls exfoliate from diaphyses; element is very fragile, falling apart (Fig. 5b)	Similar to long bones*	Bone falls apart in situ, with large splinters lying around; original element shape is difficult to determine; cancellous bone is exposed

\*Further weathering of the specimen in Fig. 5b might make the element impossible to identify

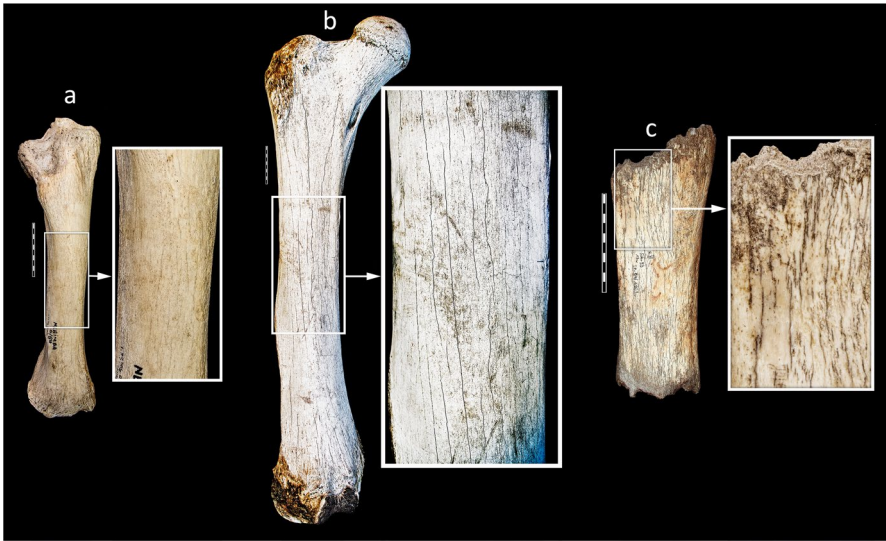
**Fig. 1** African elephant bones in WS 0, with smooth cortical surfaces and no drying cracks, about 1 year after death in Hwange National Park, Zimbabwe. The carcass was immersed in a shallow rainwater pond for several months; soft tissue and marrow are gone and the bones are being sun-bleached



**Fig. 2** Woolly mammoth humeri from the 18–11 ka site Berelekh in Arctic Siberia (Russia), in WS 0. There are no drying cracks and the surfaces are smooth. Specimens (a) and (b) have remnant cartilage on epiphyses which are oozing marrow oil; specimen (c) is no longer oozing. These bones are mineral stained and may never have been sun-bleached



dry in a lab (Fig. 9b). The two wider cracks (shown by arrows in Fig. 9b) might make the bone appear to be in WS 1–2, but the original lack of microcracks indicate that it was in WS 0 when collected. Cracks that are created by trauma in life do not continue through diaphyses into epiphyses. The carnivore-gnawed bone in

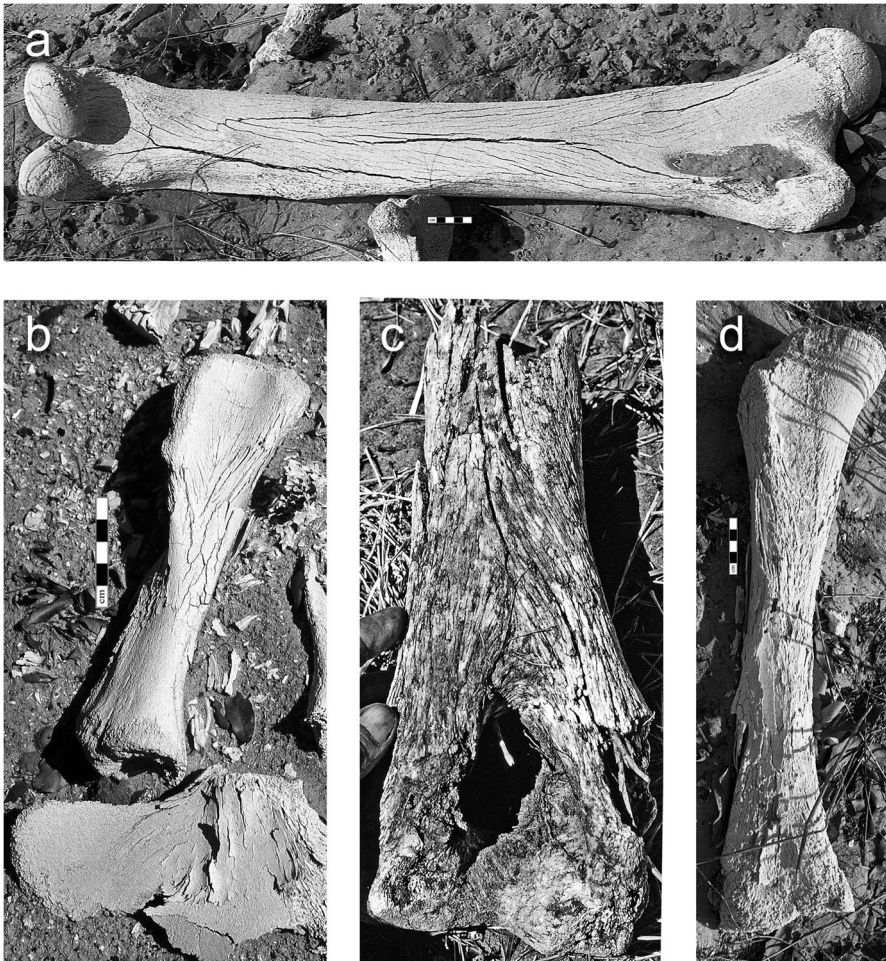


**Fig. 3** Early weathering stages on long bones of African elephant and woolly mammoth (scale bars are 10 cm). **a** Adult female African elephant tibia which had been intermittently immersed in a rainwater pond for several days at a time, in WS 0–1, a little more than 1 year after death in Hwange National Park, Zimbabwe. It has microcracking but it has not yet been sun-bleached, and soft tissue and marrow are gone. **b** Adult male African elephant femur in WS 1, a little more than 1 year after death in Hwange National Park, Zimbabwe; this bone was never in water, and it is sun-bleached, retains some dried soft tissue, and has wider cracks than the tibia in (a). **c** Woolly mammoth tibia diaphysis fragment from Deszczowa Cave (Poland) in WS 1, with carnivore gnaw marks at each end

Fig. 9c might appear to be in WS 1 or a higher stage, but we assign it to WS 0–1 because the diaphysis surface is smooth without cracking.

Drying cracks may be linear, slightly or sharply curved, or angular on some elements such as mandible and pelvis (Fig. 10). The mandible from a juvenile woolly mammoth (*M. primigenius*) in Fig. 10b was deposited 27.9–27.6 ka in the Gravettian level at the Kraków Spadzista archaeological site in Poland during Greenland Stadial 4 or 3, a cold event just before the Last Glacial Maximum (Lengyel & Wilczyński, 2018; Pryor et al., 2013; Wilczyński et al., 2019, 2020) along with thousands of other mammoth bones in a small karstic paleodepression that had sparse vegetational cover (Łanczont et al., 2015a, b, c). Its depositional context is similar to that of Zimbabwe elephant bones in open-air localities. This bone could have been exposed to subaerial weathering for several years before its burial in fine-grained sediments at the site, probably longer than the time which would be estimated for a juvenile African elephant mandible with the same characteristics in Zimbabwe.

Semi-longitudinal and linear drying cracks on the relatively straight diaphyses of elephant long limb elements may curve as they continue towards epiphyses. Bones with curved drying cracks and which are trampled will break with partly curvilinear fractures (Fig. 11) (also see Haynes et al., 2021: Fig. 16). The fracture outlines appear oblique or semi-spiral (Fig. 11a and b), and fracture surfaces may be partly



**Fig. 4** Differences in weathering of bones of adult and juvenile African elephants. **a** Femur of adult female elephant in WS 2 in Hwange National Park, Zimbabwe, with deep drying cracks that are wider than in WS 1, a visibly rougher cortical surface; and patchy cortical peeling/exfoliation on the diaphysis. **b** Juvenile elephant humerus and ilium in WS 2, with peeling patches of outer cortical bone in Hwange National Park, Zimbabwe. Drying cracks on juvenile long bones are often obscured when thin cortical layers of woven bone exfoliate. **c** Distal part of adult elephant humerus in late WS 3 in Hwange National Park, Zimbabwe, with wide cracks that have rounded edges, peeling fibers of cortical bone, and loss of cortical bone on the epiphysis. **d** Juvenile elephant femur in WS 3, with outer cortical layers lost and inner layers still peeling in Hwange National Park, Zimbabwe

smooth but are usually mostly rough (see Haynes et al., 2021 for fracture surface terminology).

Fracture fronts on fresh and unweathered bones terminate on diaphyses or at metaphyses when the bones are trampled by elephants; however, trampled dry bones may crack through metaphyses and into epiphyses (Fig. 12), unlike trauma-created cracks (see Fig. 9a).

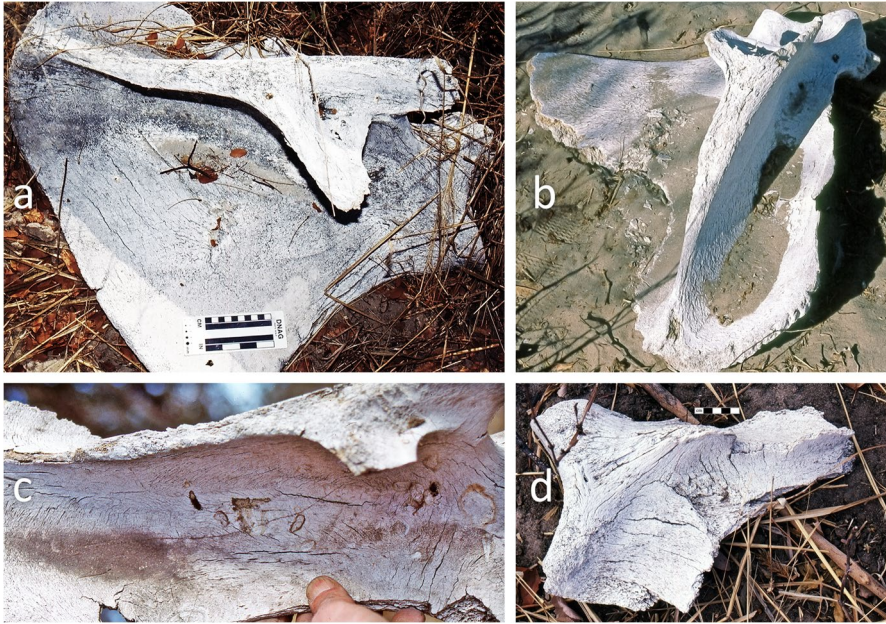
**Fig. 5** **a** Juvenile African elephant tibia in WS 4, > 12 years since death in Hwange National Park, Zimbabwe, with splinter-like peeling/exfoliating of the entire cortical surface and loss of cortical bone at epiphyses. **b** Proximal part of an African elephant scapula in WS 5, > 15 years since death in Hwange National Park, Zimbabwe, with cortical surface deeply exfoliating and larger pieces of bone crumbling off



**Fig. 6** Parts of the medial aspects of two African elephant ribs collected in Hwange National Park, Zimbabwe (scale bar is 5 cm). Specimen (a) is in WS 0, with smooth sun-bleached surface and no drying cracks. Specimen (b) is in WS 1, about 2 years since death, bleached white and with sharp-edged drying cracks



Drying cracks on weathered fossil bones may widen and lengthen if the bones are water-cleaned and dried after excavation. New cracks also may develop on originally unweathered fossils after extraction from their depositional matrix. Such recent cracks have been documented on excavated mammoth bones after water cleaning and storage. Recent drying cracks are often distinguished by a

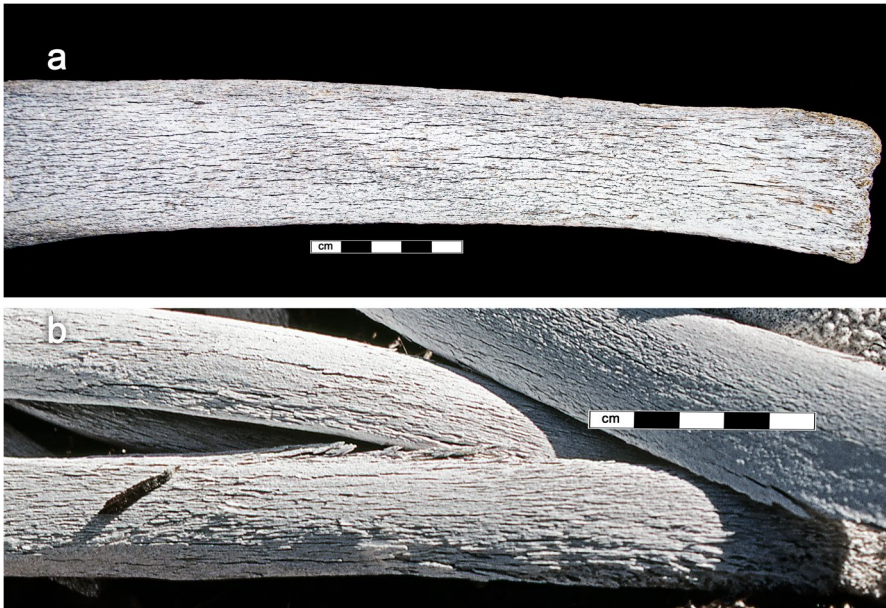


**Fig. 7** Weathered African elephant scapulae in Hwange National Park, Zimbabwe. **a** Adult scapula in WS 1, about 3 years since death, with no soft tissue and drying cracks having sharp edges. **b** Trample-broken juvenile scapula in WS 2, about 3 years since death, with a rough/flaky surface (note no visible drying cracks); the outer cortical layer in juveniles is fibrolamellar tissue, typical of growing bone, and weathers differently from the bone tissue of skeletal elements that are not remodeling as quickly. **c** Trample-broken adult scapula in WS 2, with rough surface and patchy exfoliation. **d** Trample-broken adult scapula fragment, in WS 3, with wide cracks that have rounded edges and beginning of spalling/flaking of cortical surface layers

lighter color of the crack surfaces (Fig. 13a and b) whereas original cracks created by pre-burial weathering will probably be stained the same color as the outer bone surface. Recent cracks usually have sharp edges and may be oriented mostly along the long axis of long bones or follow collagen fibril bundle orientations on other elements.

The drying of bones in storage after excavation could cause exfoliation of outer bone layers which mimics a feature of advanced weathering (WS 3+) (Fig. 13c); Gaudzinski-Windheuser et al., (2018: 10, and Fig. 6) noted “random papyraceous micro-exfoliation of the outermost bone surface” on cervid bones in the Neumark Nord 1 (Germany) fossil assemblage, similarly linking it “most likely” to “post-excavational drying.”

Elephant ribs in WS 1 or WS 1–2 may begin to split lengthwise for half or more of their length even when lateral and medial sides are differently weathered. Figure 14a and b show two elephant ribs in WS 1, and Fig. 14c shows a fragment of woolly mammoth rib in WS 1 from the Kraków Spadzista site. The fossil and recent ribs have similarly split lengthwise. The elephant ribs and the mammoth rib in this figure are not marked by trampling or carnivore gnawing, which



**Fig. 8** Weathered African elephant ribs collected in Hwange National Park, Zimbabwe (scale bar is 5 cm). **a** Rib in WS 2, from adult female elephant, about 3 years since death, with rough cortical surface having numerous drying cracks with unsharp edges. **b** Ribs from a young adult male (~25 years old), in WS 3 with peeling/exfoliation and much rougher surfaces

indicates that weathering caused the splitting. The inset in Fig. 14a is a closer view of part of the longitudinal drying crack in one elephant rib. Figure 15a and b show the wavy outlines of longitudinal drying cracks on two elephant ribs in WS 1. The cracks are directing the lengthwise splitting of the ribs into medial and lateral halves.

Longitudinal splitting might be mistaken for the results of human actions. Some parts of the crack seen in Fig. 15c and d are pseudo-notches (Haynes et al., 2021) which might be mistaken for impact notches made by percussion or pressure.

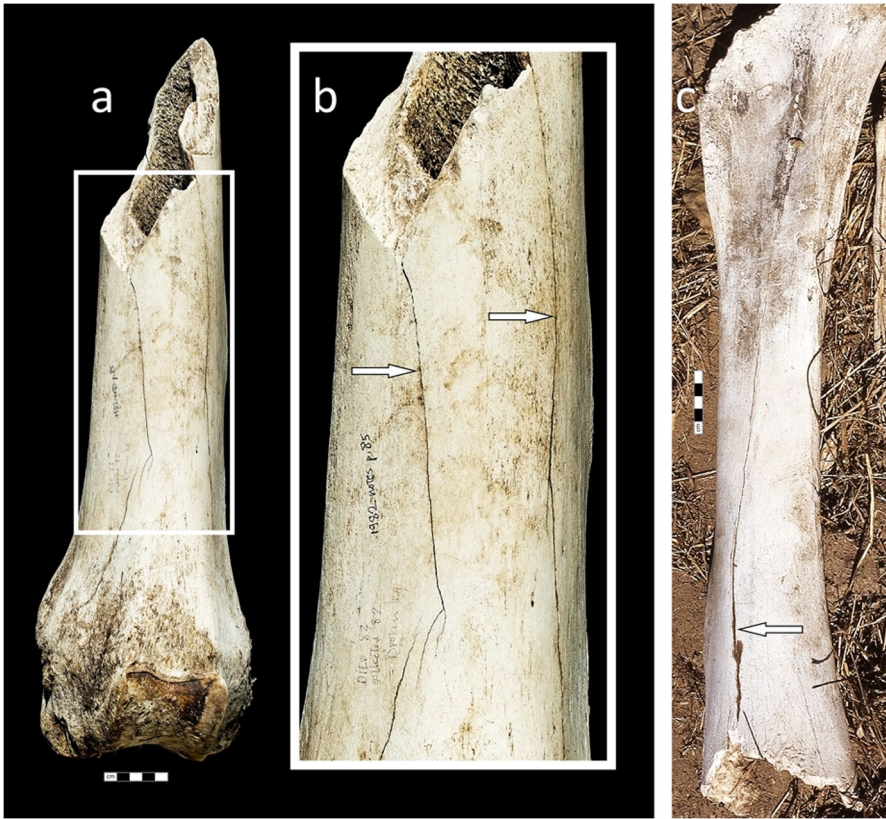
Figure 16 shows an elephant rib fragment (WS 2) that had begun to split before it was chewed by a large ungulate. The tooth marking is distinguishable from carnivore tooth marking (see Hutson et al., 2013; Haynes & Hutson, 2020).

Weathering effects on subchondral bone of the glenoid and acetabulum can differ from weathering effects on cortical surfaces of ribs and limb bone diaphyses. The surfaces where limb epiphyses articulate such as the glenohumeral joint may have a bumpy texture after hyaline cartilage disappears in WS 1 and WS 2. Examples of these changes have been observed for African elephant (*e.g.*, Fig. 17a) and woolly mammoth bone (*e.g.*, Fig. 17b). It is not known if this characteristic is more common or intense on juvenile (still-growing) bones; further study is recommended.

**Table 2** Time since skeletonization of Zimbabwe elephant bones, and estimated or measured time since death or exposure of nonproboscidean bones in other studies. The entry “na” means no data are available. Transitional stages (e.g., 0–1 and 1–2) were not formally recorded in studies done outside Zimbabwe

Weathering stage (WS)	Approx. time since skeletonization of Zimbabwe elephants in savanna and woodland	Time-since-death of elephants in African tropical rain forest (Tappen, 1994)	Time since death/exposure of nonproboscideans in African semiarid savanna (Behrensmeier & Faith, 2006; Behrensmeier, 1978)	Time since death/exposure of proboscideans in open prairie American boreal forest (Miller, 2009, 2011)
0	0–1 yr (up to 2+ yrs if “mummified,” fully shaded, or intermittently immersed in water)	Up to 16 yrs	< 1 yr	< 1 yr
0–1	1–2 yr (or longer if “mummified,” partially shaded, or in moist conditions)	Cracking does not always appear	na	na
1	1–2+ yrs (or longer if “mummified,” mostly shaded, in moist conditions)	> 10–15 yrs	~6 mos–2.5 yrs	~0.3–6 yrs
1–2	2–4 yrs (or longer if “mummified,” mostly shaded, in moist conditions)	Cracking does not always appear	na	na
2	3–8 yrs (or longer if “mummified” or mostly shaded or in moist conditions)	Cracking does not always appear	~2–5 yrs	[3–5 yrs?]-
3	4–10 yrs (or longer if “mummified” or shaded or in moist conditions)	> 15 yrs	~4–8 yrs	5 yrs (stage 2–3 transition)
4	7–10 yrs (longer if “mummified” or shaded or in moist conditions)	na	~7–20 yrs	7 or 8 yrs (stage 3–4 transition)
5	10+ to 15 yrs (longer if “mummified” or shaded or in moist conditions)	na	~10–25 yrs (> 35 yrs possible for elephants and rhinos)	7 or 8 yrs (stage 4–5 transition)

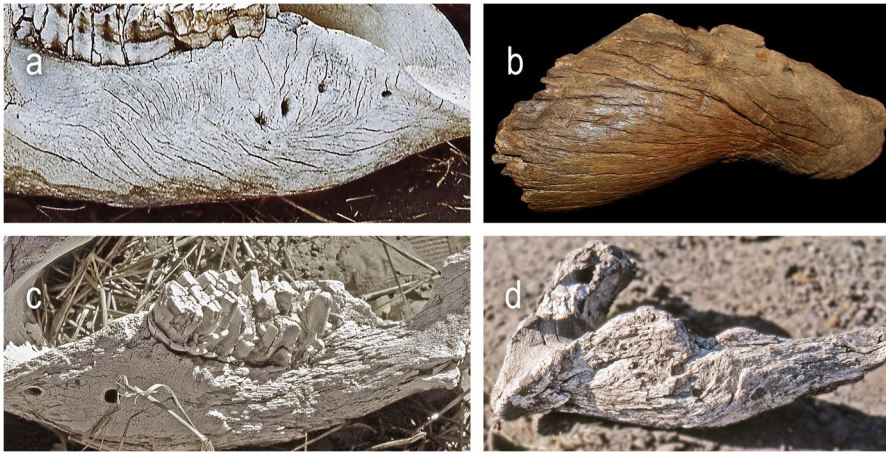




**Fig. 9** Cracks created by trauma and carnivore gnawing (scale bar is 5 cm). **a** Distal part of a traumatically fractured adult female African elephant femur in WS 0, collected ~12 months after death in Chirisa Safari area, Zimbabwe. **b** Closer view of the outlined area showing trauma-created cracks (indicated by arrows) which were seen to have widened as the bone continued to dry in storage; the cracks were not produced by weathering. **c** Femur from female African elephant which died 12–20 years of age in Hwange National Park, Zimbabwe, with a wide crack (indicated by arrow) and a microcrack created when a scavenging carnivore ate the unfused distal epiphysis (note visible tooth marks); the bone is in WS 0–1, with marrow still present and no drying cracks on most of the diaphysis except for two originating at the gnawed end. The long crack (indicated by arrow) has mineral-stained marrow grease oozing out through it

### Other Natural Processes with Effects Similar to Weathering

Some effects of burial or inundation may complicate interpretations of fossil materials. Bones buried in mineral sediments with different pH measurements will be differentially affected by leaching, erosion, and dissolution. The same goes for bones deposited in water. These conditions produce effects variously similar to or unlike those produced by subaerial weathering.



**Fig. 10** Mandibles of African elephants and woolly mammoth in advancing weathering stages. **a** African elephant mandible in WS 2, about 4 years after death in Hwange National Park, Zimbabwe, showing rough surface with curved drying cracks. **b** Woolly mammoth mandible in WS 3, from Kraków Spadzista (Poland), showing wider drying cracks with rounded edges. **c** Juvenile African elephant mandible in WS 4, about 7 years after death in Hwange National Park, Zimbabwe, showing cortical bone separating into splinter-like spalls that are peeling off. **d** Juvenile African elephant mandible in WS 5, more than 8 years after death in Hwange National Park, Zimbabwe, showing loss of thick stratified cortical layers

**Fig. 11 a** Trample-broken adult African elephant humerus in WS 2, date of death unrecorded in Chirisa Safari Area, Zimbabwe, with curvilinear fracture outline and rough fracture surfaces. **b** Trample-broken African elephant femur in WS 3, between 4 and 7 years since death in Hwange National Park, Zimbabwe, with partly curvilinear and partly longitudinal fracture outline and mostly rough fracture surfaces



## Heating/Charring

Sections of elephant bones heated in grass fires deteriorate much faster than unheated parts. When heated bones exfoliate, signs of burning such as charring (Fig. 18a) may be lost and the isolated patches of the surfaces which had

**Fig. 12** General view and closeup of the distal end of a broken African elephant femur that was dry, free of soft tissue, and had no marrow remaining when it was trampled by elephants at a Nehimba seep, a water source in Hwange National Park, Zimbabwe (scale bars are 5 cm). A linear crack is continuous through the diaphysis and distal epiphysis. The fracture edges are sharp and the fracture surfaces are rough, unlike the features of trauma-created fractures. The fragment was collected about 4 years after death. This bone was immersed in a rainwater pond (a “pan”) for a few weeks each year, and was probably in WS 0 or WS 0–1 when trampled

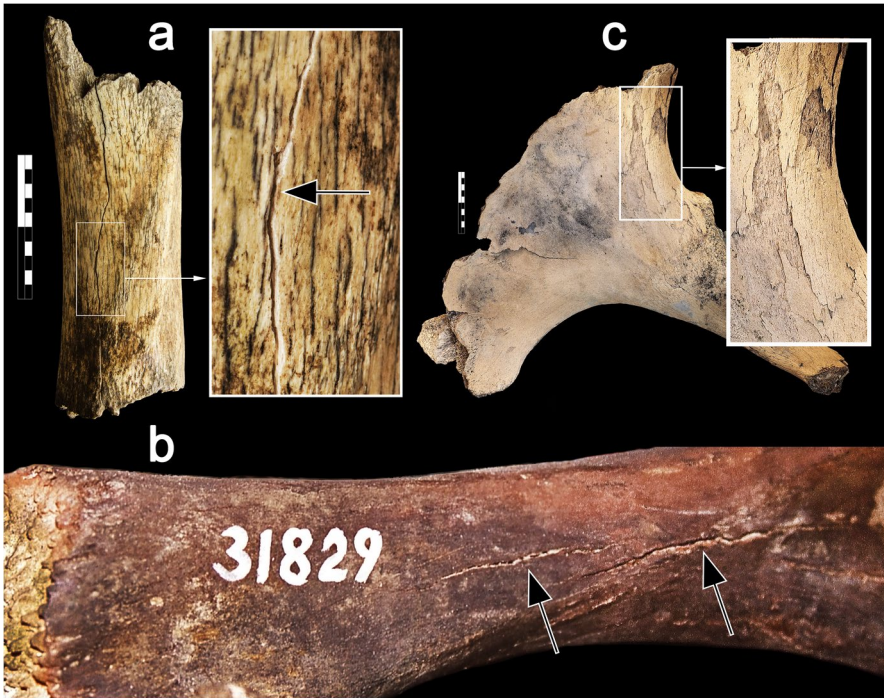


been exposed to fire will appear much more weathered than the rest of the bone (Fig. 18b and c).

### Dissolution/Erosion in Water

Green and fossil bones deposited in wet matrices or liquids are subject to differential dissolution of components. No elephant bones in waterlogged sediments or liquids were observed in the Zimbabwe study, but we suggest the possibility that proboscidean bones would show effects similar to those seen on recent nonproboscidean bones recovered from water or seasonally inundated ground surfaces. For example, the nonproboscidean bones in Fig. 19a, b, and c had lain in ephemeral pools of rainwater with alkaline pH values and the specimen at Fig. 19d was taken out of nearshore lake water with a mildly acidic pH value. Similar surface modifications have been seen on mammoth bones (Fig. 20).

Alkaline-caused cortical peeling or acid-caused efflorescence is likely on proboscidean bones deposited in liquids or waterlogged sediments with strong pH values. No examples were seen in the Zimbabwe study, but experiments with bovid bones do suggest that pH mediated modifications also might be possible for proboscidean bones. Figure 21a and b show the effects of relatively extreme pH on previously defleshed green bones of *Bos taurus*. One specimen was in a strongly alkaline solution (pH 11) and the other was in a strongly acidic solution (pH 3). Figure 21c shows the diaphyseal surface of a woolly mammoth

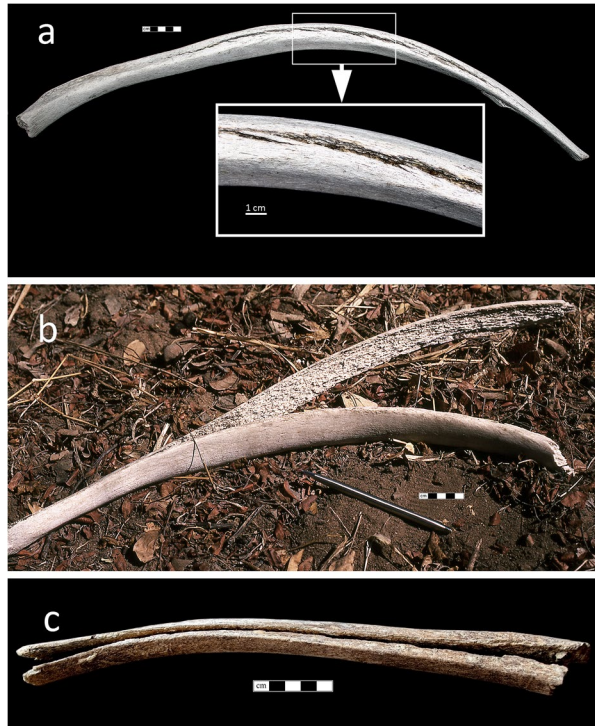


**Fig. 13** Examples of cracking and exfoliation that developed on excavated woolly mammoth bones after they were cleaned with water and dried before being placed in storage rooms. **a** Woolly mammoth tibia shaft fragment from Deszczowa Cave (Poland), in WS 1 when excavated, with a wide and deep recent drying crack (indicated by arrow); note the sharp edges of the crack and the lighter color of the fracture surface (scale bar is 10 cm). **b** Ulna diaphysis from the Khatanga woolly mammoth (“Vereshchagin’s mammoth”) (Ukrainitseva, 2013; Vereshchagin & Nikolaev, 1982) (Arctic Siberia, Russia), with two recent drying cracks, photographed in 1987 at the Zoological Institute, Saint Petersburg, Russia. The soft tissue and skin on mammoth bones at the Khatanga discovery site protected the bones from weathering, keeping them in WS 0. **c** Woolly mammoth pelvis fragment from Targowisko (Poland), in WS 0 or 0–1 when excavated, showing a large patch of peeling/exfoliating cortex

femur from the Berelekh paleontological site in Arctic Siberia. The peeling is similar to that of the modern *Bos* bone which was in the alkaline solution. The exfoliating surface might be interpreted as in WS 3, but the lack of deep drying cracks that penetrate the cortical bone suggests that the bone has been subject to chemical erosion in a relatively humid microenvironment. The bone was one of thousands deposited 14,000–11,000 rcy BP (most intensively ~ 12,300 rcy BP; Pitulko, 2011) by the Berelekh river and preserved in frozen ground. The bones were flushed out by twentieth century mammoth-bone hunters directing pressurized streams of water (Vereshchagin, 1977).

Experiments are needed to record how fresh and weathered elephant bones are affected by waters and mineral sediments with different chemistry. Future study of the effects of burial/inundation must also consider the possibility that pH/chemistry of enclosing sediments or water changed over time.

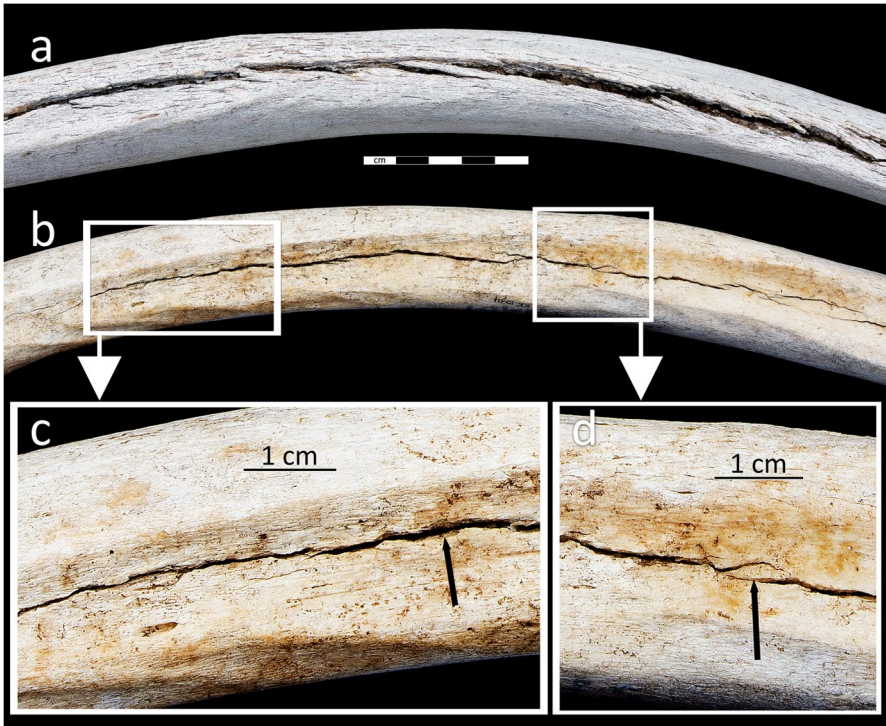
**Fig. 14** Proboscidean ribs splitting lengthwise from weathering (scale bars are 5 cm, except in the inset at **a**). **a** and **b** show two African elephant ribs from Hwange National Park, Zimbabwe; both are in WS 1 and are beginning to split in half lengthwise. **c** A Kraków Spadzista woolly mammoth rib fragment in WS 1 which has completely split into lateral and medial portions



### Root Marks a.k.a. Root Etching and Other Effects of Plant Growth

Acids which are exuded from growing or decaying vascular plant roots can create intricate convoluted networks of shallow grooves on bone surfaces (Fernández-Jalvo & Andrews, 2016: 33–34) (Fig. 22a and b). The marks are called root etching or dendritic erosion (Gifford-Gonzalez, 2018: 344). Such marks have been recorded on isolated parts of mammoth bones and also on entire surfaces of fragments or elements. Elephant bones lying atop and within moister substrates and perhaps deposited for years may be root-marked, but none were seen in the African fieldwork. Haynes recorded root-marking on recent nonproboscidean bones in temperate and subarctic regions of North America, and it is probable that buried bones were being marked. Root marking by vascular plants may obscure the early stages of surface exfoliation resulting from bone weathering. Intensive root etching could effectively destroy the outer surfaces of mammoth bones, sometimes completely, and like weathering could make it impossible to identify modifications such as cut marks left by hunters-gatherers. Plant root marks also may make carnivore gnaw marks difficult to recognize.

Another effect of plant growth was seen in temperate North American fieldwork, and it is mentioned here because it might have modified mammoth bones deposited in similar environmental conditions in the past. Thick moss growth was seen on some bones of *B.bison* in Wood Buffalo National Park (Canada) (Haynes

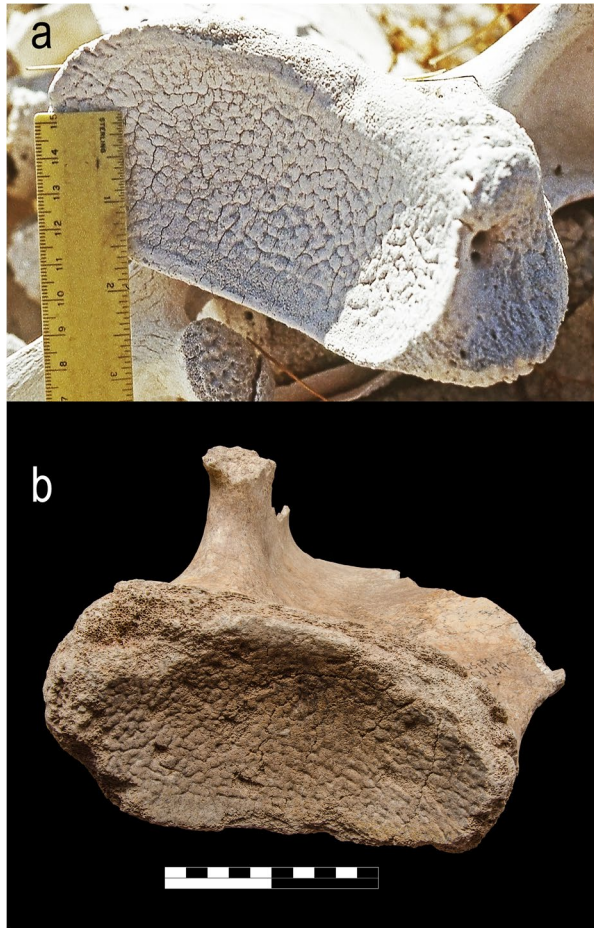


**Fig. 15** Lengthwise splitting of African elephant ribs. **a** and **b** show two ribs in WS 1 beginning to split (scale bar is 5 cm in **a** and **b**). **c** and **d** are closer views of the rib in (**b**) showing small pseudo-notches (marked by black arrows)



**Fig. 16** Two views of an African elephant rib in WS 2 that had split lengthwise before a large ungulate chewed it in Hwange National Park, Zimbabwe; note the the notch-like outline of fracture edges (scale bar is 5 cm)

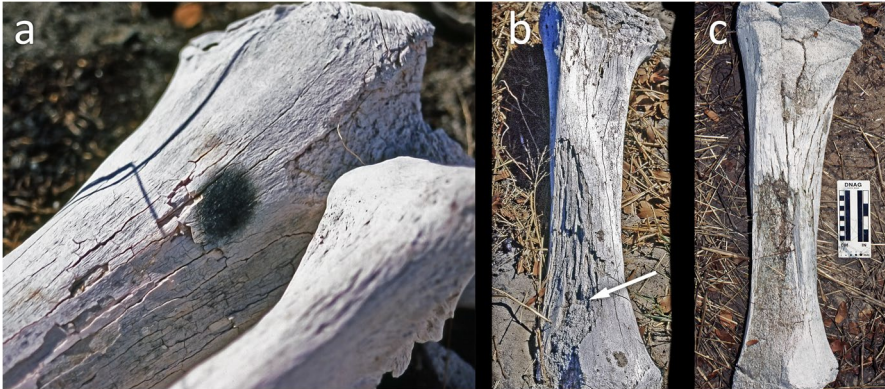
**Fig. 17** Bumpy surfaces of glenoid cavities of proboscidean scapulae in WS 1. **a** Glenoid of an African elephant scapula, about 2 years after death in Hwange National Park, Zimbabwe (scale is in inches and centimeters). **b** Glenoid of a woolly mammoth scapula from Kraków Spadzista (Poland) (scale bar is 10 cm)



unpublished data), and although the mosses did not make networks of shallow marks like plant roots do, they did promote chemical weathering which was much more intense than abiotic weathering (Crouch, 2010; Jackson, 2015)(Fig. 22c and d). Accelerated weathering of proboscidean bones due to moss growth may be possible, but no observations were recorded on elephant bones in the Zimbabwe fieldwork.

### Carbonate Precipitations/Coating

Another process that affects fossil remains is the natural coating of bones and teeth by calcium carbonate (calcite). Calcite coating may not be equivalent to calcite impregnation of bone tissue, and the two processes might indicate that bones were subjected to varying conditions during their diagenetic history (Bocherens et al., 2008). The coating process occurs after burial and affects bones from small, medium, and large mammals. Animal remains may be partly or completely covered



**Fig. 18** Effects of charring on an adult African elephant tibia after a grass fire in Hwange National Park, Zimbabwe. **a** A charred patch within a larger area of exfoliating cortical bone that also had been heated, giving the appearance of WS 3, but the rest of the element that was not so closely exposed to fire was in WS 1. **b** View of the same tibia 12 months later, in WS 2. The charred patch (arrow indicates its location before it was lost by exfoliation) and adjacent surface bone have fallen off after further weathering, and the proximal end (upper part of the image) which was also exposed to heat in the grass fire has lost cortical surface. **c** The same bone after four more years (5 years after death), showing the loss of the splinter-like exfoliating cortical bone seen in (**b**); the bone is now in WS 3, with wide rounded-edge drying cracks and peeling/exfoliation of cortical bone surfaces away from the burned area

by calcite. Calcite may be thick and make it impossible to record weathering stages or it may cover traces of human or carnivore activity. Calcite precipitations are difficult to remove so that bone surfaces can be examined for weathering stages. Figure 23 shows two sides of a calcite-coated fragment of a woolly mammoth rib from Kraków Spadzista, after some bits of crust have sloughed off or been manually removed. The exposed bone surface in Fig. 23a is rougher and seems more weathered than the other surface (Fig. 23b). Perhaps one side was skyward during subaerial weathering; alternatively, the one surface was more damaged when calcite was knocked off during Pleistocene cryogenic movement in frozen ground.

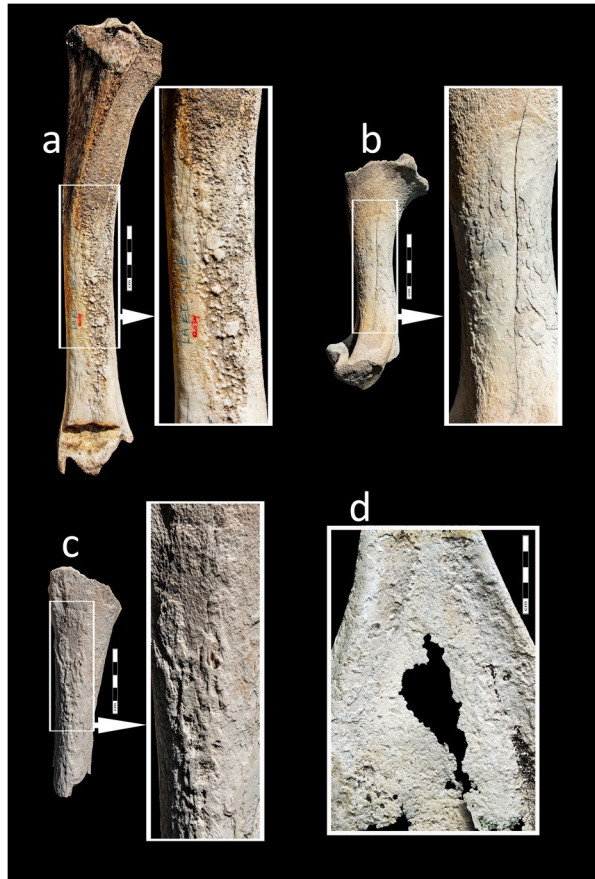
## Discussion

### Can Weathering Stages Aid in Estimating Time of Exposure?

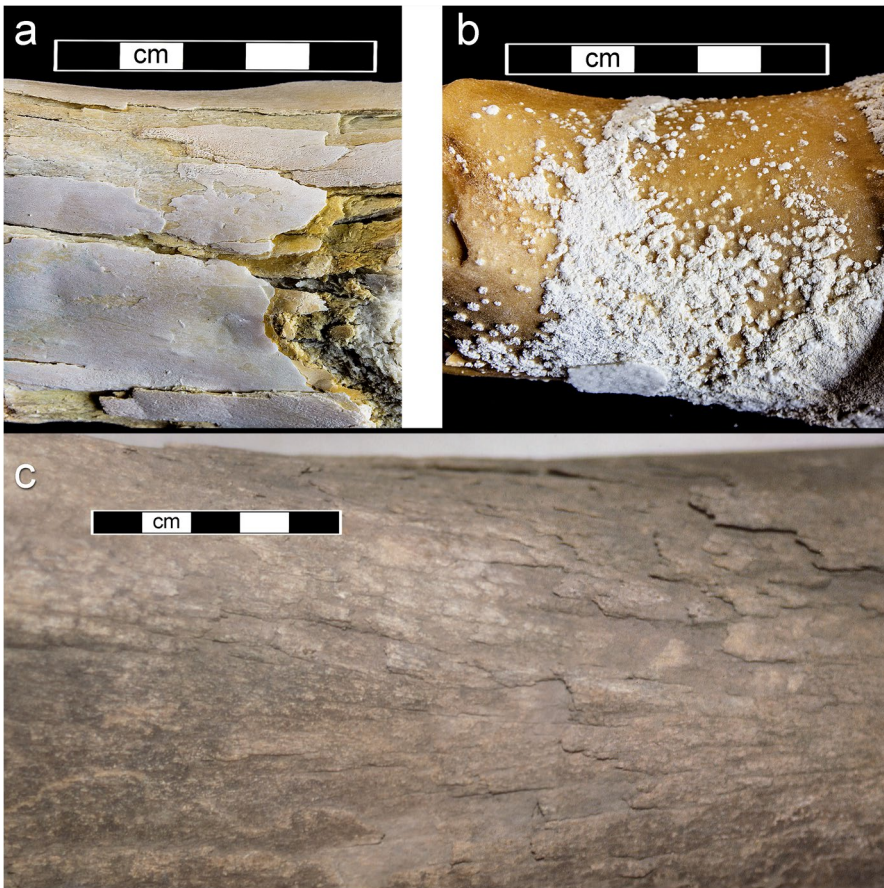
As Lyman and Fox (1989: 313) recognized, “bone weathering data do not in any simple and direct fashion reflect Time, particularly the duration of bone assemblage formation.” For example, the length of time between death and bone exposure through loss of soft tissue varies by season in many environments. A factor that must be taken into consideration when estimating time since death is how long it took for proboscidean carcasses to be skeletonized after death. This may vary greatly in different habitats and micro-environments. Therefore, estimating time-since-death is not simple or straightforward for elephant bones.



**Fig. 19** Nonproboscidean bones eroded in water with different pH values (scale bars are 5 cm). **a** Wildebeest (*Connochaetes taurinus*) tibia that was seasonally immersed in shallow pan water (pH 8–9) in Lake Mutirikwe Recreational Park, Zimbabwe. **b** Juvenile bison (*B. bison*) humerus found in seasonally flooded “Salt Plains” (pH 9–10) in Wood Buffalo National Park, Alberta, Canada. **c** Tibia fragment from cf. *Bos taurus* found on the seasonally inundated shore of Pyramid Lake (NV, USA) (pH 9.4) (Wilkie & Wood, 1996). **d** Scapula of moose (*Alces alces*) pulled from shallow near-shore water of Lake Superior (MI, USA) (estimated pH 5–6). The juvenile specimens in (b) and (c) exfoliated sooner and more severely than bones of adults because the cortical tissue had a more porous woven structure while growing

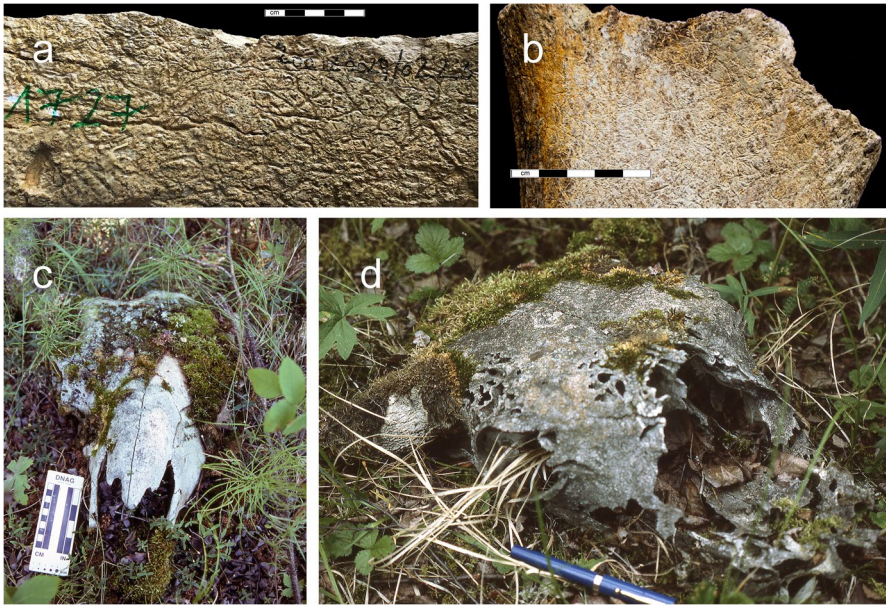


**Fig. 20** Juvenile or young adult *Mammuthus columbi* ulna proximal diaphysis with apparent surface dissolution/exfoliation; excavated from fluvial sand at Blackwater Locality No. 1 (NM, USA) (scale bar is 5 cm)



**Fig. 21** **a** *Bos taurus* bone fragment that was experimentally immersed after defleshing when green in pH 11 water solution for 1 month. **b** *Bos taurus* bone that was experimentally immersed after defleshing when green in pH 3 water solution for 48 months. **c** Close view of woolly mammoth long bone diaphysis surface from Berelekh (Arctic Siberia, Russia) with similarity to the bone surface in (a) (scale bars in (a) and (b) are 5 cm)

In Zimbabwe, subaerially exposed carcasses of elephants may not skeletonize for months, a year, or, in a few documented cases, more than a year. The thick skin and soft tissue may dry hard (that is, ‘mummify’ the remains) in the dry season if a carcass is unscavenged or only lightly scavenged by carnivores, arthropods, and microbes. On elephant carcasses, the dried skin is like “stiff armor over ... articulated bones” (Fig. 24), which is how Frison (1974: 25) described mummified non-proboscideans in the North American High Plains. The retention of skin can retard bone exposure for a long time, as woolly mammoth fur and skin might have done, thus prolonging the period before the actual exposure of bone surfaces. Dry tissue eventually disappeared from Zimbabwe elephant carcasses after annual rain rewetted the soft tissue, encouraging arthropods and carnivorous scavengers to feed



**Fig. 22** Bones affected by plants (scale bars in (a) and (b) are 5 cm). **a** Root-etched woolly mammoth bone fragment from the Epiaurignacian/Epigravettian site Langmannersdorf (Austria). **b** Root-etched woolly mammoth bone from the Gravettian site Milovice 1 (Czechia) with possible carnivore tooth marks on the right edge. **c** Moss covered bison skull in Wood Buffalo National Park (Alberta, Canada) (scale bar is in inches and centimeters). **d** Another bison skull in Wood Buffalo National Park after moss was removed, showing fragile cortical bone that was eroded by the moss (the scale is a pen ~12.5 cm long)

**Fig. 23** Two sides of a woolly mammoth rib fragment from Kraków Spadzista (Poland) (scale bar is 5 cm). **a** Thick calcite (inorganic carbonate) coat on one side of the specimen; **b** the surface on the opposite side of the specimen after some calcite crust had been manually picked off. The bone appears to be in WS 1, but might have been less weathered before the crust formed





**Fig. 24** Carcass of an adult female African elephant about three months after death in the dry season in Hwange National Park, Zimbabwe, photographed a few weeks before rains returned. The skin has dried hard over the articulated skeleton, protecting bones from weathering in the strong sunlight; muscle masses and viscera have been consumed or autolyzed, most of the trunk has been eaten by carnivores, and one foot bottom has been removed by scavenging carnivores (far right of image). Scavenging by carnivores and vultures has temporarily ceased

on remains, but months or longer may have passed since death. Carcass bones in rainwater ponds that dried up seasonally or that were lying within thick vegetation developed drying cracks after soft tissue eventually disappeared, but the signs of weathering took longer to develop than on bones in open locations.

Other factors complicate the determination of time since skeletonization in any microenvironment. The rate of transitioning between stages differs for juvenile bones. Even bones from a single *in situ* adult or juvenile skeleton may be in different weathering stages (Fig. 25). We suspect that exposed lateral surfaces of ribs weather at a different rate than exposed medial surfaces, although we do not have statistical data to support this statement and encourage future studies to confirm it. A possible reason may be differences in the cortical tissue structure of lateral and medial parts of ribs. Another possible reason for differences in the weathering stages of opposite sides of any bone is that a bone's skyward side will dry rapidly in sunlight after wetting by rain or snow, while the unexposed downward side will dry more slowly out of direct sunlight. According to Bass (1997: 184), "moisture is the greatest factor in the deterioration of bones." Forensic scientists know that wet-dry cycling of human long bones produces "differential expansion and contraction" of inner and outer cortical bone layers (Berryman et al., 1997: 167), leading to separation and flaking of circumferential lamellae. Wet/dry cycling on its own can make bones advance through weathering stages, even without the other typical components of weathering such as thermal cycles of expansion and contraction, freeze/thaw cycles, exposure to ultraviolet light, and loss of organic content (Pokines et al., 2018). Wet-dry cycling — especially when drying is rapid — is here proposed to be the main controlling factor in the rate of proboscidean bone deterioration.

Localized or stochastic events affect the extent of weathering. The signs of weathering take longer to develop on bones lying in seasonal rainwater ponds or in thick



**Fig. 25** Femora in slightly different weathering stages from an unscavenged adult female African elephant, ~12–14 months after death in Hwange National Park, Zimbabwe. The upper (right) femur is in WS 0, with no drying cracks on the diaphysis, but the lower (left) femur is in WS 0–1 with a few visible hairline drying cracks (indicated by black arrows). Both femora have small patches of remnant soft tissue. Dried skin had remained on this carcass for months until the return of rains; a possible reason for the difference in WS may be that the carcass lay in its left side and the lower (left) femur had been wetter than the right femur

vegetation, compared to bones in open locations. Thick vegetation slows deterioration by screening sunlight and delaying drying. Bones that weather for a time and then are buried by windblown or waterlain sediment may be re-exposed later and resume weathering, and also may be subsequently re-buried, thus greatly lengthening the time spent in each weathering stage. Cyclic processes of weathering which are spread through several episodes of exposure/burial/re-exposure — *i.e.*, punctuated weathering — will complicate estimates of time spent in lower weathering stages. Multiple burials and partial re-exposures also may create nonuniform weathering of single elements, as Lyman and Fox (1989: 314) suggested. As well, buried bones might be chemically affected by natural leaching, which upon re-exposure accelerates the weathering or otherwise leads to singular or unusual effects.

In summary, the length of time a recent or fossil proboscidean bone has weathered can be estimated only roughly and provisionally at best, because (1) climate and local conditions such as protective shade, aerobic versus anaerobic matrices, and seasonal differences in temperature and humidity directly affect weathering rates; (2) different elements may weather at faster rates or have different weathering characteristics; (3) re-exposure/re-burial cycles start and stop the weathering clock; and (4) weathering is a continuum without sharp divisions in the progression.

### **Bone Preservation in Different Settings**

Bones, teeth, and tusks not buried by windblown or waterlain sediments do not preserve forever, possibly only up to 25 years in open environments such as tropical

savanna and 50–200 years (or more?) in other regions with denser vegetation or lower mean temperatures before disintegrating from exposure. The stages of bone deterioration due to weathering are consistent in comparable settings, but localized conditions do have very different effects on rates.

Many biomes preserve proboscidean remains, but not even the high Arctic provides perfect conditions because weathering occurs in any exposed setting. Buried bones in all environments may be subjected to leaching and other processes that remove or replace constituents. Bones buried in permafrost may be the least altered diagenetically (*e.g.*, see Vereshchagin, 2002: 268–300), although occasional thawing of frozen ground might allow seasonal leaching or other processes affecting bone chemistry (Kirillova et al., 2021).

Other kinds of burial matrix also preserve bones that appear unweathered. For example, the salty water, mineral wax (ozocerite), and asphalt-infused silt in the Starunia oil fields of Poland (now in Ukraine) preserved the remains of woolly mammoth and two woolly rhinoceroses (*Coelodonta antiquitatis*), with date range 40.0–35.3 ka. Skin and muscle were preserved on mammoth bones; one rhinoceros carcass had much of the skin and internal organs preserved, but no horns and hooves and not much hair survived (Anon., n.d.; Kuc et al., 2012; Nowak et al., 1930). Other contexts such as rockshelters and relatively open (ventilated) caves in temperate latitudes also are known to preserve not only unweathered bones but also soft tissue because of low moisture levels, little microbial activity, protection from ultraviolet light, and reduced temperature changes. However, we should mention that abundant mammoth bone specimens from the Aurignacian assemblage in Vogelherd Cave in southwest Germany (Münzel et al., 2017) had moderate (72% of NISP) to advanced (22% of NISP) weathering (Niven, 2007: 216; Niven, 2006), possibly because many bones had been collected from open-air settings elsewhere and transported to the cave for their architectural (rather than nutritional) utility (Niven, 2006: 222); they were already weathered when deposited in the cave. Woolly mammoth remains are not especially numerous in Central European caves and rock shelters, probably because mammoth bones would have been stripped of meat and not brought to cave sites for processing due to high transport costs. In Aurignacian and Gravettian layers of sites in the Swabian Jura (SW-Germany), the number of mammoth remains varies from a few dozen to a few hundred, with the exception of the thousands of pieces representing 28 mammoths at Vogelherd Cave (Münzel et al., 2017).

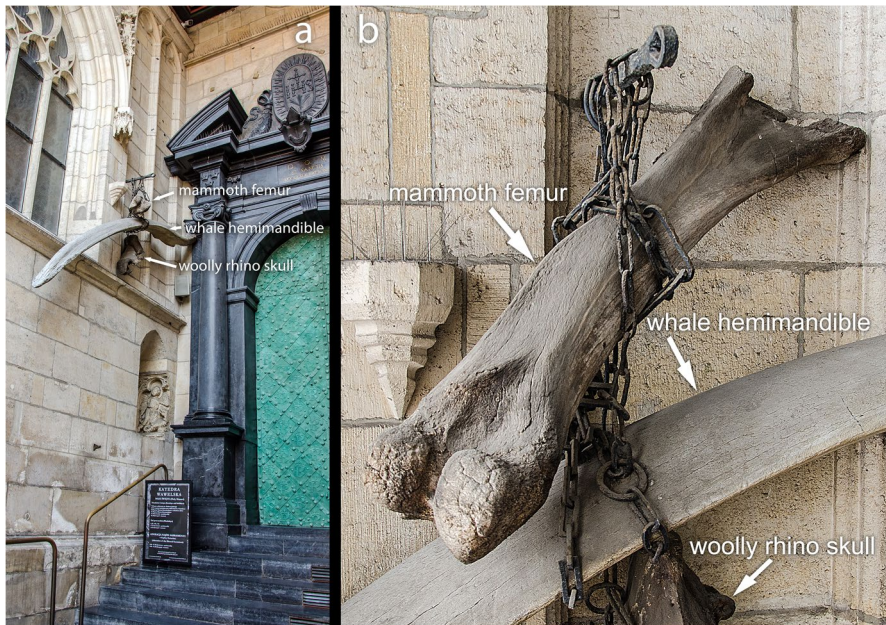
Fossil proboscidean bones are frequently found in waterlain sediments. Graham and Laws (1971:354–64) reasoned that the deposition of elephant bones in waterlain sediments may be because injured or diseased elephants stay near water and green vegetation, or weakened animals would tend to travel downhill along paths of least effort to where water accumulated. Even when African elephant carcasses or skeletons have been recorded in dry flatland expanses with loose sediments that are seasonally reworked by wind and rainwater flooding, much of the time, there have been water sources within a few kilometers (Coe, 1978; Haynes, 1991 and unpublished field notes 1983–1997).

Proboscideans need not have died within water sources for some bones to be preserved there. A fossil proboscidean skull found by itself or with other bones in a paleo-pond deposit might have been carried by living animals and dropped there

some distance away from where an animal had died. African elephants have been observed moving individual bones from elephant death sites, even the largest elements such as skulls and innominates. Poole (1992: 1983) saw elephants “actively remove elephant bones” and she suggested elephants play “an equally important role” to scavengers and trampling in dispersing elephant bones, which “their ancestors” [sic – apparently also meaning *Palaeoloxodon*, mammoths, and mastodons] did too.

### Exceptional Slowing of Weathering

The weathering of subaerially exposed proboscidean bones may be slowed in certain circumstances, as discussed above, and here we describe what we consider to be exceptional slowing of weathering. No examples were recorded in the Zimbabwe elephant study, but we have documented cases of subaerially exposed fossil mammoth bones that have hardly progressed through weathering stages after decades or centuries of exposure. Bones of extinct large herbivores and extant large mammals such as whales were once hung on the walls of Christian churches and cathedrals in parts of Europe, either inside the buildings or outside entrances, perhaps because they were thought to be giants’ or dragons’ bones. Some are still hanging outside churches, such as the large bones near the entrance of Wawel Cathedral in Kraków (Poland) (Fig. 26a), which includes a woolly mammoth left femur, the skull of a



**Fig. 26** Three large mammal bones hanging at an entrance to Wawel Cathedral in Kraków, Poland (photographed 10/2021 and 07/2015). **a** View of the bones hanging by chains. **b** Closer view of the woolly mammoth femur which appears to be in WS 1-2, although the more exposed distal part is in WS 2, with deep cracks in the diaphysis and loss of cortical surfaces on distal condyles

woolly rhinoceros (*Coelodonta antiquitatus*), and a hemimandible of an unidentified whale. The conditions of the bones and the dates when they were discovered or collected are not known, but they were most likely first hung during the Middle Ages, probably in the fourteenth or fifteenth century when the current structure was being completed. Drawings published in 1834–1839 show the bones in place over the outside entrance (Czyżewski, 2015). The bones have no visible evidence that they were ever coated with varnish or other preservatives before hanging; if some type of coating had been applied, it did not penetrate deeply into the bones. It is therefore probable either that the bones always have been unprotected or any treatment disappeared long ago. The bones have been exposed for hundreds of years, and they have experienced major daily and seasonal changes in humidity, temperature, UV light, and other environmental factors, yet their state of preservation is relatively good. The femur appears to be in WS 1–2 or WS 2, with cracks in the diaphysis, loss of cortical surface on distal condyles exposing trabecular bone, and beginnings of peeling/exfoliation on the distal postero-medial diaphysis (Fig. 26b). The proximal end of the bone might have been missing when the specimen was found or might have been broken off when the large and heavy bone was moved or hung. The woolly rhino skull hanging at Wawel is relatively well preserved, its condition similar to WS 1–2 or WS 2 for proboscidean bone, and a small part of the whale hemimandible protruding beyond the overhanging roof has exfoliating patches of the cortical surface, characteristic of more advanced weathering, comparable to proboscidean WS 3.

A similar example of such unexpected preservation of an exposed mammoth bone is also known from the wall of a fifteenth century church in Raciborowice (Poland), a few kilometers northeast of Kraków. On the outside wall above the church entrance is affixed a woolly mammoth tibia (Fig. 27) near a shield with the head of a bovid (?*Bison bonasus*) perhaps symbolizing the man who funded the church. The tibia has lost cortical bone at both epiphyses where cortex was thinnest and has drying cracks and peeling/exfoliation of the diaphysis, which are characteristics of WS 3. The bone is more exposed to the weather than the bones at Wawel Cathedral. The



**Fig. 27** A woolly mammoth tibia in WS 3 hung over a fifteenth century church door in Raciborowice, Poland (photographed 10/2021). **a** View of the bone next to a shield depicting a bovid with a nose ring. **b** Closer view of the hanging bone secured by a chain



exact date when the tibia was hung on the outer wall of church is not known, but it was probably placed there first in the Middle Ages, likely in the fifteenth century. It has no sign of ever being painted with preservative when it was originally hung. The actual time of exposure cannot be confirmed, but this fossil bone has been exposed to changing weather conditions for decades or centuries.

It is surprising that the bones mentioned above have not deteriorated further despite long outdoor exposure to variable humidity, temperature changes, and UV light. Decades (probably centuries) of weathering have affected the bones much less than predicted. The bones expectably should have progressed to higher stages of weathering after the first decades of exposure. The bones are never removed from their outdoor locations, so they have been subjected to Poland's semicontinental ("warm temperate fully humid warm summer") climatic conditions, with relatively low average number of sunshine hours per day (=Cfb in Köppen-Geiger classification; Weatherbase.com, n.d.). We submit that the most significant factor slowing the deterioration of bones at both cathedrals has been their protection from repeated and intensive wet-dry cycling. Without the partial protection afforded by being held close against church walls under roof overhangs, the outermost cortical bone layers on the hanging elements would have been periodically wetter than the deeper cortical bone after rain or snow fell, and also would have dried much sooner. More intense wetting and drying would have led to more cracking and exfoliation of outer bone surfaces than seen on the hanging elements. Even if both mammoth bones had been painted with varnish or another treatment before being hung many years ago, it is noteworthy that the mammoth bone at Raciborowice shows the more advanced weathering, which we attribute to its being more exposed than the mammoth bone at Wawel.

### **Would Weathered Bones Have Been Useful as Paleolithic Raw Material?**

Weathered proboscidean elements may have been chosen as Paleolithic raw material because of potentially useful sizes and shapes. Münzel (e.g., 2001; Münzel et al., 2017) described pointed objects made from split mammoth ribs in the Gravettian levels of Hohle Fels and Geißenklösterle Caves (Germany) and postulated that the ribs had been split by humans. The mammoth rib specimens from Hohle Fels and Geißenklösterle Caves show no signs of cutting and scraping along edges, although such marks had been created on an Asian elephant's defleshed ribs when experimenters started a replicative process of making artifact blanks from ribs (Münzel et al., 2015); however, "almost all mammoth rib fragments and ribs in mammoth/rhino size from Gravettian layers show traces of working" (Münzel et al., 2017:191). A specimen from Hohle Fels has faint marks thought to be similar to the effects of a wedge driven into the cancellous interior to split the rib (Münzel et al., 2015). Another archaeological site in central Europe, Kraków Spadzista (Poland), has > 4700 fragments (NISP) from > 1500 mammoth ribs (MNE) (Wojtal unpublished data) in the site's primary disposal area (Zone III) (Wilczyński et al., 2012: 3638). Some fragments were from split ribs and have pointed ends and fracture edges that appear notched. Figure 28 shows three views of split mammoth rib fragments in WS 1 from the site. These might be interpreted as blanks for making bone



**Fig. 28** Three views of each of three split woolly mammoth rib fragments in WS 0–1 or 1, from Kraków Spadzista (scale bars are 5 cm). Arrows indicate arcuate fracture edge segments that appear to be notches

points, such as are present in Gravettian assemblages in the German caves, but we question that possibility. The specimens do have pointed ends and fracture edges which look notched, as if they had been prepared for splitting, but they also are similar to modern proboscidean ribs which commonly split this way when they dry and begin to weather (see Figs. 14 and 15). The curving parts of fracture outlines may be pseudo-notches. A large number of mammoth rib fragments were found at the site, including three notched, incised, and/or polished specimens, but no rib points have been identified. Direct evidence at the site indicates flint points rather than bone points were used to hunt mammoths (Kufel-Diakowska et al., 2016; Wojtal et al., 2019).

Although there is no clear evidence that split ribs were further shaped into finished points at Kraków Spadzista, a partly split mammoth rib (Fig. 29) with a pointed and polished end was found at Pavlov I (Czechia), a Pavlovian site a few thousand years older than Kraków Spadzista. Thus, we acknowledge that split-rib pointed objects may be found in Paleolithic assemblages. We propose that Paleolithic foragers might have selected ribs already splitting from early weathering to use as raw material for manufacturing implements such as points. We also suggest that taphonomic analysts must be cautious when attributing the splitting of mammoth ribs exclusively to anthropogenic actions.

### Time-Averaging of Bone Assemblages

Some locales may preserve palimpsests of multiple proboscidean skeletons, effectively time-averaging the assemblages. Waterside settings and uplands with rapid sedimentation rates might quickly bury bones and thus effectively restrict bone-weathering to early stages in spite of extensive time-since-death. Bone preservation in these matrices may be consistent and almost uniform for all specimens over long stretches of time. Bones deposited and then buried far apart in time would be in the same weathering stages and perhaps appear to be of one age. Separation of death events would not be discernable if based solely on weathering or the estimated rates of weathering published in this and other papers.



**Fig. 29** A pointed mammoth rib implement from the Pavlovian site Pavlov I (Czechia) (scale bar is 10 cm). **a** Two views of the partially split rib fragment, showing the opposite cortical surfaces are in different weathering stages. **b** Closer view of the endosteal side of the pointed and polished end. **c** Closer view of the unweathered (WS 0) bone surface. **d** Closer view of the weathered (WS 3) surface

## Weathering Analysis of Fossil Assemblages

Our aim with this paper is not to contradict published interpretations of fossil proboscidean bone assemblages, but to present data which might refine interpretations where possible. Here, we demonstrate the relevance of weathering analysis for understanding assemblage origins by discussing three fossil proboscidean assemblages: Colby (Wyoming, USA), a Paleoindian site with bones of Columbian mammoths (*M. columbi*) and associated lithic material; Kraków Spadzista (Poland), an Upper Paleolithic site with remains of woolly mammoths (*M. primigenius*) and other mammals along with thousands of associated lithics; and Ambrona (Spain), a Middle Paleolithic site with bones of *Palaeoloxodon antiquus* and associated lithics.

Colby in the western USA contained bones of seven Columbian mammoths (*Mammuthus columbi*), six lithic projectile points, two of which were found in mammoth-bone piles, a lithic flake tool, and 31 lithic flakes, all but one recovered from within mammoth-bone piles (Frison, 1986). The materials were found in channel bottom deposits, arroyo side slopes, and anthropogenically created bone piles. Todd and Frison (1986: 38) surmised that bones with concentric layers of exfoliation had deteriorated after burial, due to soil conditions or “other factors,” while the bones with penetrating cracks in their surfaces had weathered before burial. Todd and Frison (1986: 39) also surmised that bones with only one weathered surface had lain undisturbed on ground surfaces before burial. Our data support these possibilities, although we suggest that the concentric exfoliation of

some Colby mammoth elements might be due to ephemeral wetting and drying of buried material which could have happened before excavation.

Todd and Frison (1986:40) thought that a bone weathering analysis “of the entire [Colby] assemblage would be useful in refining interpretations of the relative movement of bones” in the site’s different geomorphic contexts (channel bottom, arroyo side slopes) compared to the bones in the anthropogenically created bone piles. In the case of Colby, the mammoth bones were generally too deteriorated to discern weathering stages of most specimens, but such a complete analysis is recommended for other assemblages with better preserved bone in different stratigraphic contexts.

The late Gravettian archaeological level at Kraków Spadzista in Poland has so far yielded > 15,200 woolly mammoth bones from a minimum of 113 individuals. Stratigraphic studies indicate most mammoth bones were deposited in a paleodepression (Łanczont et al., 2015a, b, c). Only a small proportion of the bones (~ 1.38%) have visible traces of weathering such as cracks, and about half of them are in an early weathering stage (WS 1); ~0.7% have the cracking and flaking indicative of WS 2 and 3 (Wojtal unpublished data). A small fraction were exposed for carnivores to gnaw (~ 3.2% of bones have tooth marks; Wojtal unpublished data) or for animals or people to trample (~ 1.4% of bones have trampling marks; Wojtal unpublished data). Most bones apparently were protected from weathering by one or several factors specific to the site such as protection from wet-dry cycling, perhaps by rapid burial in loess or by thick vegetative cover.

The Ambrona site in Spain contained several excavated levels with lithics and bones of large mammals including *Palaeoloxodon antiquus*. Villa et al. (2005) analyzed bones of an adult male *Palaeoloxodon* found in deposits left in a swamp or shallow lake; also in the deposits were a heavily weathered tusk and an elephant mandible with no weathering cracks (Villa et al., 2005: 231) but with compression fractures. Sánchez-Romero et al. (2016) concluded that the elephant bones Villa analyzed had been rapidly buried, although they also had been “exposed to erosion and transporting process, but not for long” (Sanchez-Romero et al. 2016: 22). We do not know if proboscidean tusks and bones weather at significantly different rates and thus might have very different end-effects of weathering after similar lengths of time. The visibly different weathering of the Ambrona tusk and bones might have resulted from weathering for similar lengths of time, or it might indicate exposure for significantly different lengths of time. Therefore, we recommend further field studies of elephant materials which might account for differential weathering of bones and tusks, which would add precision to the “not for long” notation in the Ambrona interpretations.

Our data do not argue against the existing interpretations of the assemblages discussed above; however, we suggest that applying data specific to proboscideans in further analytical studies of those and other fossil assemblages will add new interpretive details. For example, results of future studies might allow more reliable inferences about whether tusks and bones excavated from the same matrices had weathered for different lengths of time, making the assemblage’s interpretations more comprehensive.

## Conclusion

This paper has summarized proboscidean bone weathering patterns recorded in a dry tropical region which has warm summers, cool winters, and seasonal rainfall. The weathering patterns may or may not be universal. The data have been offered for taphonomists to consider when analyzing proboscidean assemblages. The WS designations may make it simpler for different analysts to be consistent when classifying proboscidean bone weathering and may provide useful clues about the local micro-environments of deposition and possibly timespans involved in the origins of assemblages. We submit that the most influential factor slowing the deterioration of proboscidean bones is protection from wetting and drying, especially if the drying is rapid and cycling is repeated.

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The authors confirm they have approved this manuscript and agree to its submission to the *Journal of Archaeological Method and Theory*.

## Declarations

**Conflict of Interest** The authors declare no competing interests.

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