Quaternary Science Advances 12 (2023) 100112

Contents lists available at ScienceDirect

Quaternary Science Advances

journal homepage: www.sciencedirect.com/journal/quaternary-science-advances

Bone weathering in an Atlantic environment: preliminary results of the Global Weathering Project in Spain

A.B. Marín-Arroyo[a,*], Borja González-Rabanal[a], Jose Luís Arteche[b], Pilar Fatás[c], Manuel R. González Morales[d]

[a] *Grupo de I+D+i EvoAdapta (Evolución Humana y Adaptaciones durante la Prehistoria), Dpto. Ciencias Históricas, Universidad de Cantabria, Av. Los Castros 44, 39005, Santander, Spain*
[b] *AEMET - Agencia Estatal de Metereología, C/ Ricardo Lorenzo S/N, 39071, Santander, Spain*
[c] *Museo Nacional y Centro de Investigación de Altamira, Santillana del Mar, Cantabria, Spain*
[d] *Instituto Internacional de Investigaciones Prehistóricas de Cantabria (IIIPC), (Universidad de Cantabria-Gobierno de Cantabria-Santander), Av/Los Castros 52, 39005, Santander, Spain*

ARTICLE INFO

Keywords:
Fossil bone assemblages
Experimental taphonomy
Archaeozoology
Iberia

ABSTRACT

Weathering constitutes one of the most investigated taphonomic processes for understanding the formation of archaeological and palaeontological assemblages. Despite being studied for decades through numerous monitoring experiments, no homogeneous methodology exists to compare the results obtained in different regions and climates. Here, we present the protocols and the preliminary results of an experimental research started four years ago in a coastal and inland location within the Cantabrian Region (northern Spain) to assess the influence of the weathering process in an Atlantic climate. This experiment allows evaluation of the preservation of faunal assemblages in regional open-air sites throughout the Middle and Upper Palaeolithic. We conduct this experiment within the Global Weathering Project of the International Council for Archaeozoologists (ICAZ), an international network of archaeozoologists and taphonomists who coordinates the same experiment worldwide. The experiment planned to last 18 years consists on recording the weathering stages suffered on the cow ribs disposed on the surface of a fenced enclosure under the protection of a cage, separated from the soil by a neutral inorganic substrate and close to a weather station where the temperature, humidity, rainfall, wind and sun exposure values are daily recorded.

1. Introduction

After A. K. Behrensmeyer's pioneering publication in 1978, bone weathering has become one of the most common modifications investigated in Taphonomy to assess the formation and alteration processes suffered by any fossil assemblage. Weathering is the process by which physical and chemical agents alter, sometimes up to the destruction of the skeleton's organic and inorganic components (Behrensmeyer, 1978; Trueman et al., 2004). The alterations produced by surface weathering are, usually in this order, cracking, splitting, exfoliation, dehydration, and finally, disintegration (Fernández-Jalvo and Andrews, 2016). They are produced due to changes in temperature, humidity, sunlight exposure, water precipitation and wind impact. Nevertheless, the type of soil on which the remains are placed, the time exposure and the body size and skeletal part of the specimen significantly determine the degree and speed of the bone modifications (Lyman, 1994). Weathering stages (0–5), initially defined by Behrensmeyer (1978) for medium-large mammalian vertebrates, have been traditionally used for estimating bone surface exposure. However, the different climates can favour or inhibit the gradual weathering stages (Andrews, 1990; Tappen, 1994; Andrews and Whybrow, 2005). Besides, weathering can affect bone preservation both on the surface and within the sediment, such as chemical weathering (Lyman and Fox, 1989).

Up to date, long-term and shorter monitoring experiments have been carried out worldwide. Behrensmeyer pioneered the observations in a tropical savannah climate at the Amboseli National Park (Tanzania) (Behrensmeyer, 1978). Shortly after, monitored specimens in the temperate climates of Neuadd (Wales) and Draycott (England) showed slower weathering rates compared to those initially offered by Behrensmeyer (Andrews and Cook, 1985; Andrews and Armour-Chelu, 1998).

* Corresponding author.
E-mail address: marinab@unican.es (A.B. Marín-Arroyo).

https://doi.org/10.1016/j.qsa.2023.100112
Received 29 April 2023; Received in revised form 26 July 2023; Accepted 1 August 2023
Available online 5 August 2023

Fig. 1. Location of the experimental stations on the North Atlantic coast of Spain. A) Coastal experiment in AEMET headquarters, in Cueto (Santander, Cantabria). B) Inland experiment in Altamira Museum (Santillana del Mar, Cantabria). Red arrows show the location of the cages. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Later, between 1984 and 1998, Andrews and Whybrow (2005) monitored a continuous experiment on a camel skeleton in Jebel Barakah (Abu Dhabi) in a mid-latitude desert climate. Their experimentation revealed that weathering was substantially less rapid than that recorded in tropical climates, probably due to the drastic changes in temperatures and humidity. Between 1986 and 1988 thousands of faunal bones were exposed in a tropical forest of the Virunga National Park (RD Congo), documenting a slower weathering process than in open savannah spaces (Tappen, 1994). Exposure to sunlight, type of soil, wet and dry conditions were factors attested to be involved in the increase speed of weathering advent and the appearance of higher stages. Experiments in temperate mountain environments have also been carried out, such as the red deer and fallow deer carcasses deposited in Riofrio, Segovia (Cáceres et al., 2009) or in cold periglacial climates near the poles, such as the island of Qikirtaq, Nunavik (Canada) (Todisco and Monchot, 2008). As a result, under temperate and cold conditions, weathering lowest stages are the most represented ones.

Other researchers focused on experimental and naturalistic observations have investigated weathering processes from different points of view. Trueman et al. (2004) investigated the mineralogical soil composition and the changes that reflect the process phases in the trace elements and how the type of sediment -where the remains lay-influences weathering appearance and proliferation. Madgwick and Mulville (2012) applied a multivariate statistical analysis to explain which archaeological variables are involved in the presence of one weathering stage or another and which taxa and anatomical elements are more likely to be affected by this taphonomic process. Vietti (2016) quantified the rough texture of each weathering stage using the Ra measured (industrial standard for profile average roughness calculated by averaging vertical deviations of estimated points from the mean line of the roughness profile) in a 3D scanner. A statistical relationship between the percentage of Ra and each weathering degree was obtained by Vietti enabling the application of new quantitative techniques to the qualitative descriptions of each phase of the process. In summary, all these experiments show that weathering increases over time and varies with climate, with modification speed depending on environmental conditions such as rainfall, sun exposure, wind influence, and drastic changes in temperature and humidity.

During the 3rd Taphonomy Working Group meeting of the International Council for Archaeozoology (ICAZ), held in Argentina in 2014, taphonomists agreed to advance this research by designing an identical long-term experiment in different parts of the world. There, simple protocols were established to have the possibility to achieve easily and later compare the weathering process results to evaluate the incidence of different climates in bone alteration. From this perspective, the Global Weathering Project (GWP), led by Alexander Parkinson, Yolanda Fernández Jalvo and Peter Andrews, was initiated by the Taphonomy Working Group of the ICAZ in 2017 and designed following Behrensmeyer protocols, but reducing the number of parameters that may influence the data.

Here, we present the results of the ongoing bone weathering experiment started in May 2019 in Cantabria (Northern Spain), a region highly inhabited throughout Prehistory (Straus, 2015) with an Atlantic climate. The area consists of a strip of land, approximately 350 km long, between the Pyrenees to the east and the River Nalón in the centre of Asturias to the west, and 30–50 km wide, between the Atlantic Ocean in the north and the Cantabrian Mountains, with peaks of about 1500–2600 m above sea level, to the south. The total surface area is about 14,000 km^2. However, during the Late Glacial, because of the fall in sea level, the region would have included an additional band of the continental platform, between 4 and 12 km wide; on the other hand, large areas of the highest massifs would have been glaciated (Marín-Arroyo, 2009). This geographical, ecological and cultural area contains one of the richest archaeological records of the Palaeolithic and Mesolithic of Western Europe, in caves and rockshelters, where open-air sites are scarce (García Codrón, 2004). The influence of weathering may be a potential cause for the low representation of open-air human occupations, where usually abiotic elements are found but biotic ones are absent. In addition, weathering rates can be slightly modified by the sea spray effect, which re-deposited sea salt over coastlines. Aerosols with specific amounts of sulphates are present in maritime regions, such as the Cantabrian Region, influencing the environment up to 30 km to the coast depending on wind direction and topographic factors (Wadleigh et al., 1996).

2. Materials and methods

The experiment on the northern coast of Spain aims to deposit animal bones outdoors to observe how and to what extent sunlight, wind, rain and changes in temperature and humidity affect bone conservation throughout time. Particularly to know how weathering affects the bones deposited in the archaeological sites of a geographical area with an oceanic climate, with temperate and humid conditions, as well as to know the differences between coastal and inland sites and the influence of sea proximity on bone preservation. To do so, this experiment is being achieved in two open-air locations: 1) Cueto (Santander), located on the current coastline, and 2) Altamira Museum (Santillana del Mar), 6 km further inland (Fig. 1).

Protocols. GWP participants were asked to leave 24 semi-defleshed cow ribs (still with periosteum, grease, marrow and some flesh) at each site on the soil surface to record the environmental influence. The ribs were placed under the protection of a stainless-steel cage to prevent

Table 1
Maximum, minimum and mean values of the climatic parameters recorded in each experimental station.

Climatic parameter	Measurement	Inland experimental station (Altamira)	Coastal experimental station (Santander)
Temperature (°C)	Max	18.3	18.1
	Mean	14.4	15.4
	Min	10.6	12.6
Humidity (%)	Max	95.3	91
	Mean	78.6	78.3
	Min	61.8	65.5
Rainfall (mm)	Mean	4	3.4
Wind (km/h)	Mean	7.6	16
Sun exposure (h)	Mean	–	5.9

small rodent and carnivore modifications. The ribs were separated from the soil by a neutral inorganic substrate to avoid the incidence of vegetation and pH soil. In addition, the ribs are inside of fenced sites to prevent modifications of people or large carnivores. These safeguard measures were taken to isolate the physicochemical processes from other taphonomic agents.

Data collection. The experiments are located in open-air enclosures with adjacent weather stations owned by the Spanish Meteorological Agency (Agencia Estatal de Meteorología, AEMET) that allow the collection of the following climatic parameters: air temperature, relative humidity, total rainfall accumulated over time, wind direction and sun exposure. Minimum and maximum temperatures are measured with an alcohol and a mercury thermometer, respectively and expressed in °C. Minimum and maximum rates of relative humidity are recorded by a psychrometer and expressed in %. The accumulated rainfall is stored with a Hellman pluviometer and expressed in mm, while the total path of the wind is measured with a cup anemometer and expressed in km. The daily sun exposure is recorded by a heliograph and described in h. The raw data available in the Supplementary Information show the mean value per day, while Table 1 and Fig. 2 show the evolution of the environmental parameters by mean values per month.

Monitoring. Simultaneously, monitoring was divided into two

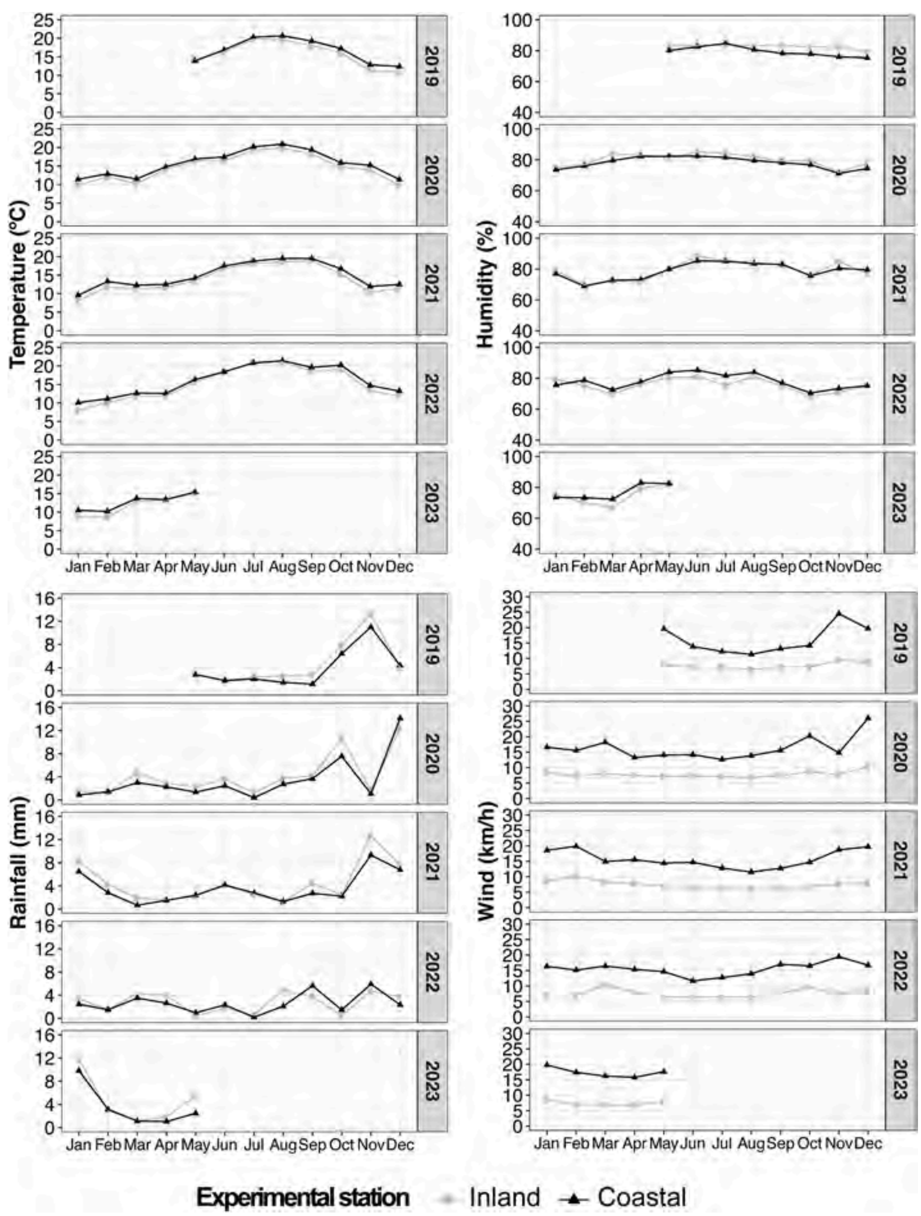

Fig. 2. Preliminary environmental parameters recorded by the weather stations (mean values per month are shown). The black triangles and grey squares correspond to the coastal and inland experiments, respectively.

Fig. 3. Different stages of the decomposition process in the cow ribs used for this study. A) Fresh; B) Bloat; C) Active decay; D) Advanced decay; E) Skeletonization; F) Fine cracking marks on the bone surface.

different tasks periodically conducted. Firstly, three ribs are monitored as specimen controls to register all the macroscopic traits during the whole experiment. Regular inspections are conducted monthly, photographing the ribs, recording the macroscopic changes suffered in their bone surfaces and comparing them with the meteorological data. Secondly, ribs extraction being carried out to remove, store and register the accurate changes seen at each monitoring stage. Thus, a rib was removed every four months during the first year of experimentation and subsequently, a rib has been extracted annually during the initial four years. Consequently, the investigation may last up to 18 years.

3. Results

Environmental parameters were recorded during the first four years of experimentation. Those parameters show similar temperature and humidity patterns between both experimental stations (Table 1, Fig. 2). There are no drastic changes between both. However, slight differences are observed. The average temperature is lower in the inland experiment (Altamira) than in the coastal one (Santander). In the same way, the maximum temperature is similar in the inland and coastal experiments, unlike the minimum temperature, which is lower in the inland than in the coastal one. Concerning the humidity parameter, the average remains slightly higher in the inland than in the coastal one. The maximum humidity is also higher in the inland than in the littoral, while the minimum moisture is higher in the coastal than in the inland. Alternatively, the rainfall and the wind proxies show stronger contrast between both sites. There is more rainfall in the inland than in the coastal. Conversely, the wind travels more km in the seaside location, blowing stronger and faster than in the inland place. Finally, the sun exposure could only be measured in the coastal experiment, showing a mean value of 5.9 h per day. This data reflects a relatively low sun exposure, which should also be similar in the inland place.

During this time, we removed six ribs in total in each experimental station (4 ribs during the first year and one each year). Up to now, we have already recorded all the stages of the decomposition process: fresh, bloat, active decay, advanced decay and skeletonization (Fig. 3). Preliminary results show that the decomposition speed of the organic matter still left in the ribs varied due to the environmental factors where they are located (Fig. 4), being slightly slower on the coast than in the experimental station located inland. Our results indicate that the skeletonization phase appeared before in the inland experiment than in the coastal one. Despite this variation, the first cracking marks start to be visible in both places, albeit weakly (Fig. 3).

Carnivore or rodent modifications have not been identified, remarking the protection the enclosure provides to the ribs. Only the microorganisms and insects' activities directly related to decomposition and environmental factors have been identified. We detected fly eggs, maggots, fungus, microroots, moss or lichens. However, the neutral inorganic substrate protects the bones from the soil and vegetation.

4. Discussion and conclusions

The meteorological data collected by the weather stations do not show significant differences between the two places of experimentation. The coastal experiment shows slightly lower humidity, higher temperature, lower rainfall, and more wind. These climatic conditions produce a slower decomposition rate of the ribs' organic matter, suggesting that air salinity could be an additional factor delaying the speed of decomposition and the beginning of the weathering modifications in the coastal station. However, once the organic matter was decomposed, the ribs from both experimental stations showed the same degree of weathering. After four years of exposure, most ribs do not have any weathering modification (stage 0) in both locations. However, some thin and superficial marks are beginning to appear in four ribs in the inland station and two ribs in the coastal one (stage 1). They are parallel to the fibre structure and longitudinal to the rib bones.

Given the climatic and environmental conditions of the Atlantic coast of Spain, it is possible to compare this experiment with those carried out in temperate climates such as the Neuadd (Wales), Draycott (England) and Riofrío (Spain). In Neuadd, most elements do not show any sign of weathering after 30 years of experiment, and the few bones that show some alteration were classified in low weathering stages (1–2), none of them ever reaching the maximum degree of the condition. Furthermore, many of the bones were corroded by rainwater falling on

Fig. 4. Monitoring of a specimen control from the coastal and inland experiments during the first four years of the experimentation.

them before they were affected by any weathering stage (Andrews and Armour-Chelu, 1998). Similarly, in the Draycott experiment, no evidence of weathering after eight years of monitoring was observed in the bones due in part to the nature of the site, a rockshelter surrounded by vegetation with low sun exposure. This case could be used for comparisons with karstic environments, where the weathering modifications are similar (Andrews and Cook, 1985). The study of Riofrío (Segovia, Spain), in a temperate mountain environment, is similar to the British experiments, but some bones reached the weathering stage 3 after 16 years of experiment, although most presented low weathering stages (Cáceres et al., 2009).

Despite the first fine cracking marks being visible after four years in our experiment, we assume that the most abundant degrees will be the lowest (0–2), considering the cited experiments. Our preliminary results, in conjunction with the absence of the highest degrees of weathering in experiments conducted in temperate climates, suggest that the weathering process would be much slower than in other warmer environments (Behrensmeyer, 1978; Tappen, 1994; Andrews and Whybrow, 2005). In this sense, other alteration agents such as pH soil, vegetation or even sedimentation may begin to alter the archaeological records before weathering reaches its highest stages or bones disappear (Lyman and Fox, 1989). Therefore, weathering modifications cannot be the only explanation for the region's lack of prehistoric open-air sites and probably is related to a multicausal phenomenon (Fernández-Jalvo and Andrews, 2016).

In conclusion, this is the first time that a weathering project is being achieved on the North Atlantic coast of Spain, and it will last 14 years more. Preliminary results reveal a slower decomposition rate of the attaching organic matter, and, therefore, a slower emergence of weathering processes in the coastal experiment, suggesting that air salinity might play a key factor. However, the ongoing investigation will provide new data to corroborate or refute this hypothesis in the following years. AEMET climatic records is allowing us to compare those data with the weathering stages in each experimental station. Finally, more research is needed in multiple environments to generate a more comprehensive Global Weathering Project to understand the weathering processes better worldwide.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are available at the GitHub repository at https://github.com/ERC-Subsilience/Global_Weathering_Project_NSpain

Acknowledgements

This research is funded by the European Research Council under the European Union's Horizon 2020 Research and Innovation Programme (grant agreement number ERC CoG-818299; SUBSILIENCE project; https://www.subsilience.eu) and the Government of Cantabria - Department of Universities, Equality, Culture and Sports 2022–2023. We also thank Altamira Museum and the Spanish Meteorological Agency (AEMET) for the facilities provided during the performance of the experiments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.qsa.2023.100112.

References

Andrews, P., 1990. Owls, Caves and Fossils: Predation, Preservation and Accumulation of Small Mammal Bones in Caves, with an Analysis of the Pleistocene Cave Faunas from Westbury-sub-Mendip. University of Chicago Press, Somerset, UK.
Andrews, P., Armour-Chelu, M., 1998. Taphonomic observations on a surface bone assemblage in a temperate environment. Bull. Soc. Geol. Fr. 169, 433–442.
Andrews, P., Cook, J., 1985. Natural modifications to bones in a temperate setting. Man 20, 675–691.
Andrews, P., Whybrow, P., 2005. Taphonomic observations on a camel skeleton in a desert environment in Abu Dhabi. Palaeontol. Electron. 8, 1–17.
Behrensmeyer, A.K., 1978. Taphonomic and ecologic information from bone weathering. Paleobiology 4, 150–162.
Cáceres, I., Esteban-Nadal, M., Lluc Bennàsar, M. de, Fernández-Jalvo, Y., 2009. Disarticulation and dispersal processes of cervid carcass at the Bosque de Riofrío (Segovia, Spain). J. Taphon. 7, 129–141.
Fernández-Jalvo, Y., Andrews, P., 2016. Atlas of Taphonomic Identifications: 1001+ Images of Fossil and Recent Mammal Bone Modification. Springer, London.
García Codron, J.C., 2004. El marco del poblamiento paleolítico: unidad y diversidad de los espacios cantábricos. Kobie 8, 11–28.
Lyman, R., 1994. Vertebrate Taphonomy. Cambridge University Press, Cambridge.
Lyman, R.L., Fox, G.L., 1989. A critical evaluation of bone weathering as an indication of bone assemblage formation. J. Archaeol. Sci. 16, 293–317.
Madgwick, R., Mulville, J., 2012. Investigating variation in the prevalence of weathering in faunal assemblages in the UK: a multivariate statistical approach. Int. J. Osteoarchaeol. 22, 509–522.
Marín-Arroyo, A.B., 2009. Exploitation of the montane zone of Cantabrian Spain during the Late Glacial. Faunal Evidence from El Mirón Cave. J. Anthropol. Res. 65, 69–102.
Straus, L., 2015. Recent developments in the study of the Upper Paleolithic of Vasco-Cantabrian Spain. Quat. Int. 364, 255–271. https://doi.org/10.1016/j.quaint.2014.05.008.
Tappen, M., 1994. Bone weathering in the tropical rain forest. J. Archaeol. Sci. 21, 667–673.
Todisco, D., Monchot, H., 2008. Bone weathering in a periglacial environment: the Tayara site (KbFk-7), Qikirtaq island, Nunavik (Canada). Arctic 61, 87–101.
Trueman, C.N.G., Behrensmeyer, A.K., Tuross, N., Weiner, S., 2004. Mineralogical and compositional changes in bones exposed on soil surfaces in Amboseli National Park, Kenya: diagenetic mechanisms and the role of sediment pore fluids. J. Archaeol. Sci. 31, 721–739.
Vietti, L.A., 2016. Quantifying bone weathering stages using the average roughness parameter Ra measured from 3D data. Surf. Topogr. Metrol. Prop. 4, 034006.
Wadleigh, M.A., Schwarcz, H.P., Kramer, J.R., 1996. Isotopic evidence for the origin of sulphate in coastal rain. Tellus B: Chem. Phys. Meteorol. 48, 44–59.