Citation for final published version:

Madgwick, Richard ORCID: https://orcid.org/0000-0002-4396-3566 2014. What makes bones shiny? Investigating trampling as a cause of bone abrasion. Archaeological and Anthropological Sciences 6 (2) , pp. 163-173. 10.1007/s12520-013-0165-0 file

Publishers page: http://dx.doi.org/10.1007/s12520-013-0165-0 <http://dx.doi.org/10.1007/s12520-013-0165-0>

Archaeol Anthropol Sci
DOI 10.1007/s12520-013-0165-0

ORIGINAL PAPER

What makes bones shiny? Investigating trampling as a cause of bone abrasion

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Received: 14 October 2013 / Accepted: 13 November 2013

Abstract Taphonomic modifications on animal bones have the potential to provide a wealth of information on the depositional histories of faunal assemblages. However, certain modifications have received little attention and their interpretation remains complex due to their varied or uncertain aetiology. This has hindered progress in approaches to taphonomic research and it remains relatively rare that a comprehensive suite of modifications is recorded during zooarchaeological analysis. Abrasion, defined as a shine or polish on bone, is one such modification, with a plethora of processes having been cited as a potential cause. Relatively little holistic analysis of archaeological specimens has been carried out and consequently the interpretative potential of the modification is yet to be realised. This paper examines the degree to which the process of trampling causes bone abrasion. Trampling causes multiple, sub-parallel, linear striations on bones and has been suggested by some researchers as a cause of abrasion (see Andrews and Cook, Man 20:675–691, 1985; Behrensmeyer et al., Palaeogeogr Palaeocol 63:183–199, 1986; Fiorillo, Univ Wyoming Contrib Geol 26:57–97, 1989; Myers et al., Am Antiquity 45:483–490, 1980; Nielsen, Am Antiquity 56:483–503, 1991; Olsen and Shipman, J Archaeol Sci 15:535–553, 1988). Research presented here involves statistical analysis of a large and diverse faunal dataset from seven British sites. Results from both correlation and logistic regression analysis demonstrate the very close relationship between the two modifications, although this is not the case at every site. These findings strongly suggest that trampling is a major cause of abrasion in a British context. Once the relationship is established at a specific site, the modification can be more reliably used for reconstructing the taphonomic trajectory of an assemblage.

Keywords Taphonomy · Abrasion · Trampling · Site formation · Multivariate statistics · Regression

Introduction

Taphonomic modification in zooarchaeology

The analysis of taphonomic modifications is increasingly recognised as crucial to the valid and reliable interpretation of faunal assemblages. Taphonomic data is vital for reconstructing site formation and for identifying processes which have altered faunal assemblages. Analysis of modifications is crucial for modelling data loss, in terms of species, elements and butchery marks that may be underrepresented due to the taphonomic filters through which an assemblage has passed. It is also of considerable use for reconstructing sequences of deposition and prescribed modes of treatment of classes of material (see Madgwick 2008, 2010; Orton 2012; Redfern 2008; Russell 2010; Symmons 2005). However, patterns can only be interpreted with a thorough knowledge of the factors affecting the prevalence of a modification, both surrounding its aetiology and the inherent susceptibilities of the classes of bones it impacts upon (see Madgwick and Mulville 2012). Variation in modification prevalence may result from the different properties of a certain class of remains being conducive to a specific modification rather than being indicative of human agency.

Detailed studies on certain modifications and agents of accumulation have greatly improved understanding of different taphonomic processes in recent years (e.g., Domínguez-Solera and Domínguez-Rodrigo 2009; Hutson et al. 2013; Krajcarz and Krajcarz in press; Lloveras et al. 2012;

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Madgwick and Mulville 2012). This paper focuses on two modifications that have received less attention: trampling and abrasion.

Abrasion and trampling

Abrasion is defined as erosion of a bone's surface by any agent, through physical force (Bromage 1984) and is characterised by smoothness, sometimes progressing to a glossy polish on fragments through the removal of external lamellar bone (Behrensmeyer 1982). Some researchers have used abrasion as an umbrella term for natural modifications such as ablation, pitting and cracking (e.g., Thompson et al. 2011), but it generally pertains to the rounding of fracture edges and a smoothness or polish on bones. Abrasion should not be confused with acid erosion, which creates a rough surface texture. Abraded broken edges become smooth and rounded (Behrensmeyer 1988; Fernández-Jalvo and Andrews 2003), surface detail is lost (Behrensmeyer 1990), bone becomes thinner (Pinto Llona and Andrews 1999, p. 420) and cortices appears polished (Thompson 2005, p. 72), although they may appear rough at a microscopic level (Bromage 1984).

Causes of abrasion are diverse and have been suggested to include human and animal movement (Brain 1981, p. 15; Lyman 1994, p. 381), carnivore licking and digestion (Andrews 1990; Haynes and Stanford 1984), pathological conditions (Bartosiewicz 2008, p. 75), tool manufacture/use (Buc 2011; Fisher 1995, p. 31), earthworm activity (Armour-Chelu and Andrews 1994, p. 433), roasting (Coy 1975, p. 428), bioturbation (Haynes 1980, p. 350) and prolonged transport (Argast et al. 1987). Movement in an aqueous setting is also a major cause (Bromage 1984; Denys 2002, p. 475; Fernández-Jalvo and Andrews 2003; Nicholson 1992, p. 80; Parsons and Brett 1991; Thompson et al. 2011). Boiling can also cause abrasion, through the rubbing of bone against the side of pots (Fisher 1995, 31). In addition low energy trampling by rodents can abrade bones (Haynes 1980, 349), as can the repeated handling of skeletal material (Bromage 1984). Accurate recognition of abrasion is rarely challenging, although identifying the exact cause is difficult. Bromage (1984) attempted to characterise the micromorphology of different sources on forming bone but results proved problematic. This experimental research demonstrated that initial modification was similar regardless of the agent of abrasion, even when analysed microscopically and is characterised by the removal of superficial mineral or cortical bone (ibid., p. 166). Similarly, prolonged/extensive abrasion provides uncharacteristic modifications for defining aetiology, even at a microscopic level, with indentations and surface lamellae removed (ibid., p. 164). Without being able to determine the aetiology of the modification, its interpretative potential is severely limited. Therefore new approaches to establishing the cause are required.

Trampling has generally been marginalised in zooarchaeological research (Behrensmeyer et al. 1989, p. 117; Blasco et al. 2008, p. 1605), but is recognised as a major cause of fragmentation and artefact dispersal. However, these criteria do not provide direct evidence of trampling, as both have diverse aetiologies. The best direct evidence for trampling takes the form of shallow, sub-parallel striations (Andrews 1995, p. 148; Andrews and Fernández-Jalvo 1997, p. 199; Behrensmeyer et al. 1986; Courtin and Villa 1982; Fiorillo 1989; Nielsen 1991; Olsen and Shipman 1988), but in some instances it can also cause notches on oblique fracture angles (Blasco et al. 2008). Striations do not result from direct contact with hooves, as they are in fact softer than bone. They rather result from friction with sedimentary particles during movement caused by trampling by medium/large mammals or humans. Consequently, certain sediments are more conducive to trampling evidence (Nielsen 1991). Effects tend to be more severe in sandy, abrasive matrices though not all research is in agreement (Behrensmeyer et al. 1989; Denys 2002: 475; Fiorillo 1989). In some instances, friction with minute bone particles may also cause striations (Bromage 1984, p. 166). Experiments indicate that striations observable with low-power magnification may only be useful for identifying high intensity trampling, with the identification of earlier effects being more complex (Domínguez-Rodrigo et al. 2009). However, in the author's experience the incidence of this modification is relatively common in archaeological deposits, depending on the character of the site's sedimentary matrix. Experiments by Domínguez-Rodrigo et al. (2009, p. 2650) have demonstrated a strong correlation between striation prevalence and both exposure duration and sediment coarseness.

Unlike abrasion, the confident identification of trampling is problematic. Striations can be confused with cut-marks (Andrews 1995, p. 148; Behrensmeyer et al. 1986; Bunn 1981; Fiorillo 1984, 1989; Lyman 1994, p. 377; Oliver 1989; Olsen and Shipman 1988, p. 535; Potts and Shipman 1981) and tool use/manufacture (Buc 2011). However, trampling evidence can be differentiated, as it tends to create a large number of closely spaced, fine, shallow striations per specimen and the range of variability (in terms of depth, width and direction) is considerable (Andrews 1995, p. 148; Andrews and Cook 1985, p. 683; Olsen and Shipman 1988). The subtlety of this modification means that it can easily be masked by other processes and consequently tends to be very rare in poorly preserved assemblages.

The majority of previous studies on abrasion and trampling have involved experimental research on modern and/or archaeological bones, either through controlled trampling or fluvial abrasion, often as part of a broader taphonomic study (see Andrews 1995; Blasco et al. 2008; Fernández-Jalvo and

Andrews 2003; Fiorillo 1989; Thompson et al. 2011). Other research has focused on the microscopic characterisation of modification (Bromage 1984; Domínguez-Rodrigo et al. 2009). Whilst these studies are of great importance and have certainly improved understanding of the processes, it is crucial that assessments are made of how the modifications manifest themselves in the archaeological record.

Focussing analysis on the interplay of the modifications in the archaeological record will establish whether abrasion is a useful criterion to identify trampling. Trampling is an important taphonomic filter that can have a dramatic effect on the character of archaeological deposits. It is an almost ubiquitous feature on sites with human settlement and therefore assessing the extent of its effect is crucial for establishing the integrity of deposits and the potential for spatial studies (Clarke 1977). However, as Nielsen (1991, p. 484) states, trampling is a category of human activity (and also human-mediated animal activity) in its own right and should not be seen only as an incidental occurrence. It has considerable interpretative potential in defining the varied use of space and can aid in establishing the functional use of different areas. However, the subtle nature of trampling modifications and the susceptibility of striations to overprinting by other processes means judging the impact of trampling is problematic. Abrasion tends to occupy a larger area of a bone's surface and is therefore less easily obscured by processes such as weathering and gnawing. If a strong relationship between the processes can be demonstrated at a given site, then abrasion may provide a useful proxy for trampling. At present abrasion data is of limited use for determining agents responsible for deposit formation because of its varied aetiology. Of the potential causes cited above, only trampling and digestive corrosion leave modifications that can be macroscopically identified and therefore the relationship between modifications can be assessed. Digestive corrosion was very rare in the sample analysed for this research and in any case can be discounted from responsibility in the vast majority of cases, as it could only affect very small fragments in assemblages that derive from periods where large carnivores were almost entirely absent.

This research builds on actualistic and microscopic studies by using bivariate and multivariate statistics on a substantial sample of faunal material from seven British archaeological sites to assess the relationship between trampling and abrasion. It cannot provide a definitive answer as to the degree to which trampling causes abrasion, as this is certain to be site-specific. This research rather represents a focussed case study to assess the strength of the relationship at seven British sites, with the aim of extending the potential of abrasion data, by establishing whether trampling is central to its aetiology on a site by site basis.

Materials and methods

The sample

Analysis was carried out on a large and diverse dataset of approximately 29,000 specimens from seven sites in Britain (see Fig. 1). This dataset comprised 24,768 specimens that could be identified to element level and a further 4,267 long bone fragments that could not be identified beyond the level of medium or large-sized mammal. The taxonomic composition of the identifiable assemblage is presented in Table 1. Summary details on the sites included in the sample are presented in Table 2. All bones were recorded during the author's PhD, one aim of which was to characterise depositional histories at later prehistoric middens in southern Britain. Therefore there is a bias toward this site type but a wide range of material was analysed in terms of period, species, element and context type. In any case, midden assemblages are frequently rich in modification and therefore provide fertile ground for studies on the dynamics of bone modification.

Data collection

All analysis was undertaken under the light of a 60-W lamp and using a 10× or 20× magnification hand lens as required. Where necessary ambiguous specimens were also analysed using low power microscopy (40× magnification).

Abrasion was recorded as present when an area of at least 1 cm^2 exhibited a loss of surface texture and was visibly smooth or polished (Fig. 2). In addition presence was recorded for smoothed and rounded fracture surfaces. As the process need not occur in a linear pathway and has a potentially varied aetiology, the application of a staged recording strategy (see Davies et al. 1989; Fiorillo 1988) was considered inappropriate and presence/absence recording protocols, that have previously been successfully used (Meldahl and Flessa 1990), were employed. Evidence of abrasion was noted for all recordable elements except for teeth (which frequently exhibit a polished appearance regardless of abrasion) and also for unidentifiable diaphyseal fragments of at least 4 cm in length.

Trampling was also recorded as present or absent. The modification was only recorded when multiple, sub-parallel, linear striations covering an area of more than 1 cm^2 were observed (see Fig. 3). These provide the best evidence for trampling that can be recorded during zooarchaeological analysis (rather than on excavation). Efforts were made to differentiate cut-marks from trampling scratches following the guidance of Blasco et al. (2008: 1606) who found that trampling striations usually appear abruptly cut off and do not generally show evidence of thinning, indicative of directionality. In ambiguous specimens low power microscopy was also used to identify the presence of micro-striations indicative of cut-marks (Domínguez-Rodrigo et al. 2009: 2651).

Fig. 1 Location map of the sampled sites

Table 1 Taxonomic composition of the identifiable assemblage from each site

	East Chisenbury	Eldon's Seat	La Sagesse	Llanmaes	Navan Fort	Potterne	Whitchurch	Total
Pig	48	66	121	5367	923	1019	401	7945
Caprine	296	671	222	1643	120	2648	1252	6852
Cattle	102	589	407	1084	755	1193	769	4899
Horse	6	15	96	57	25	27	36	262
Cervid	1	25	19	72	13	21	16	167
Carnivore	5	6	52	27	2	26	24	140
Human	2	4	1	42	0	8	8	65
Lagomorph	0	0	1	4	0	2	55	62
UNID Med mammal	44	114	78	2735	4	626	208	3809
UNID Large mammal	15	39	77	200	1	192	41	565

Figures represent the Number of Identified Specimens (NISP). The simplified species categories employed in regression models have been used here (see Section 2.3). Each species category was incorporated in regression models except for unidentifiable medium or large mammal, as these were considered too vague. These specimens were all ribs and vertebrae and therefore their element categories were still included in the models

Table 2 Summary details of the sites included in the sample, including information on matrix character

	Site type	Phase	Whole/Sample	Matrix character	Reference
East Chisenbury	Midden	Late Bronze Age/Early Iron Age	Whole	silt/clay/loam	McOmish et al. (2010)
Eldon's Seat	Midden	Late Bronze Age/Early Iron Age	Sample	clay/loam	Clare Randall, pers. comm.
La Sagesse	Stream deposits	Iron Age/Medieval	Whole	tufaceous	Green (1994)
Llanmaes	Midden	Middle Bronze Age–Late Iron Age	Whole	silt/loam/clay	Adam Gwilt, pers. comm.
Navan Fort	Hilltop enclosure	Iron Age	Whole	sand/clay/loam	Waterman (1997)
Potterne	Midden	Late Bronze Age/Early Iron Age	Sample	sand/silt/loam	Macphail (2000)
Whitchurch	Midden	Late Bronze Age/Early Iron Age	Whole	clay/gravel/sand/silt	Waddington and Sharples (2011)

All midden sites comprised at least some deposits with humic, ashy anthropogenic soils, in addition to the matrices noted in the table. The fourth column indicates whether the whole assemblage was analysed or just a sample

Trampling was recorded for all identifiable elements except for teeth, which can exhibit striations resulting from wear. It was also recorded for unidentifiable long-bone diaphyseal fragments of at least 4 cm in length.

Statistical analysis

All statistical analysis was undertaken using IBM SPSS 20. First, Spearman's rank-order correlations were used to assess the co-occurrence of the two modifications. Tests were undertaken on a combined dataset of identifiable specimens and unidentifiable long bone fragments. These analyses were undertaken at both an intra- and inter-site level to ascertain whether other causes of abrasion prevailed at certain sites and whether the character of the sedimentary matrix was important in dictating the relationship between the modifications. In previous classification tree analysis, it was demonstrated that site was the most important variable (excluding other modifications) in mediating both trampling and abrasion (Madgwick 2011), and therefore it was crucial to deal with each site separately. Separate tests were not carried out for each taxon and element category as these variables were shown to have a lesser impact on modification. The inter- and intra-site analysis brings about repeat testing of components of the same dataset. This means that tests are not entirely independent of each other and therefore increases the chance of type I error, the erroneous rejection of the null hypothesis. To ensure interpretations were based on robust results only, a conservative Bonferroni correction (Rice 1989) was applied, meaning that the accepted p value of <0.05 was divided by the number of tests analysing components of the same dataset. A total of eight correlation analyses were undertaken and therefore a p value of <0.006 was required for significance to be achieved.

The strength of relationship between the two modifications was further assessed using binary logistic regression models. This analysis facilitated the incorporation of a far broader range of variables as independent factors that may relate to the prevalence of modification and provides an important complement to a simple bivariate correlation. Regression modelling provides a robust tool for assessing the impact of a range of variable categories, as the associated effects of all other categories are controlled in analysis. It can therefore assess whether other modifications indicative of sub-aerial exposure (e.g., weathering, gnawing) show a similar relationship to abrasion/trampling as the two modifications do to each other. Similarly, the degree to which contextual and zooarchaeological variables affect the prevalence of abrasion and trampling can be compared. Element, species, site, age, phase, deposit type and taphonomic categories were incorporated in analysis. In order to retain substantial sample sizes in each category, morphologically similar elements and taxa were grouped in analysis (e.g., long bones, pelvis/scapula, carnivore, cervid). This made for a complex series of

Fig. 2 Example of abrasion on a caprine tibia diaphysis. The shiny, reflective area represents a loss of surface texture due to abrasion (photograph: author)

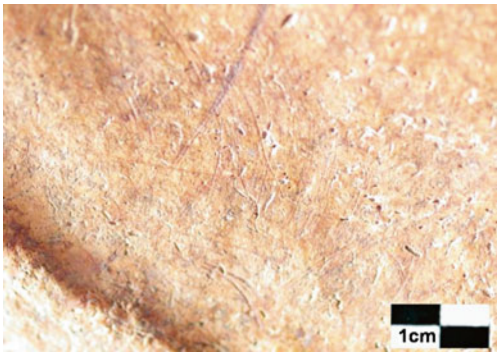

Fig. 3 Example of trampling striations on a cattle mandible. Note the close spacing and sub-parallel alignment of the multiple striations (photograph: author)

regression models, each incorporating 40 independent variables. Some variable categories, such as those relating to chronological phase were less likely to have a significant effect, but it was deemed best not to prejudge results and omit variables based on expectation.

This mode of analysis enabled a more thorough investigation of the interplay between modifications and facilitated a comparison with the effect of other variables pertaining to the character of faunal material. As all variable categories were incorporated in models, only the dataset of identifiable specimens was analysed, as most variables could not be defined for the unidentifiable long bone assemblage.

Analysis effectively assesses the degree to which the presence of each variable category (e.g., radius, pig, Llanmaes, unfused epiphysis, weathered) affects the prevalence of a given modification in the model, whether negatively or positively (i.e., generates more or less modification). Stepwise backwards conditional binary logistic regression models were employed, as the aim of analysis was to begin with a complex multivariate model that would be reiterated to eliminate unimportant variables, thus producing an optimal, simplified model. A positive effect on prevalence (shown by a positive coefficient and a p value <0.05 in SPSS output) indicates a close relationship between a variable category and a modification whilst no significant effect indicates that the two variables are not closely related. A significant negative effect indicates that the presence of a variable in the model causes (or correlates with) a reduction in modification prevalence. This means that a variable category is either resistant to modification (e.g., a specific species or element) or that one modification such as weathering acts to overprint and thus obscure a more subtle modification such as trampling. Odds ratios were consulted to assess the strength of effect.

Conducting tests on a large and varied dataset is critical for valid interpretation and reduces the likelihood of findings resulting from sampling bias. However, such a large dataset also creates problems in interpretation. Incorporating in excess of 24,000 cases into analysis provides a highly statistically powerful dataset and consequently little variation from expected patterns of modification is required for significant results to be obtained. Therefore modelling the entire dataset is certain to provide more significant results than are meaningful. Consequently a modified bootstrapping approach was employed (Efron 1982), whereby each regression model was re-tested using reducing random samples until the model breaks down. Tests were conducted on the whole dataset and on random samples of 10,000, 5,000, 2,500, 1,250, 625 and 312 cases. Two series of models were run, one using abrasion as the dependent variable and one using trampling. As in the correlation analysis, a Bonferroni correction was employed as the same dataset was continually retested. Consequently, a far more stringent p value of <0.0036 had to be attained for variables to be deemed significant in each model. This provides a very conservative mode of testing but ensures the robusticity of results. Variable categories were ranked in terms of their strength of effect on the basis of the number of significant results they produced.

Results

Spearman's correlation results are presented in Table 3. Overall a strong positive correlation was evidenced between the presence of abrasion and trampling. When testing the whole dataset, the correlation was very strong ($p<0.001$). However, site-specific tests demonstrate that the patterns were not in accordance across all assemblages. Five of the seven sites analysed exhibited a strong positive correlation between abrasion and trampling, all having p values of less than 0.001. Analysis of data from La Sagesse showed a close correlation but failed to attain the stringent Bonferroni corrected significance value and therefore patterns are not deemed significant. Navan Fort was the only site to show no correlation between the occurrence of the two modifications.

Regression models provided support for the correlation analysis in demonstrating a close relationship between the two modifications, even when incorporating a broad range of variables. Tables 4 and 5 summarise results from the two series of regression models. Unsurprisingly models that tested the whole dataset or a large random sample provided a large number of significant results. However, employing the resampling approach clarified the consistency of the effect of each variable in the series. In the first series (Tests R1–R7), abrasion was set as the dependent variable. Trampling was the only variable to have a consistent effect on the model, providing significant positive results in all seven tests. This indicated that the presence of trampled specimens in the sample had a strong significant effect on the occurrence of abrasion. The only other categories to produce significant results in at least half of the models were 'weathering', 'pig' and 'Potterne' all of which had a positive effect on modification in four of the seven models. The second series employed trampling as the dependent variable. Results clearly demonstrated abrasion as the most important variable in the series. It produced highly significant positive results in all of the models. Only two other variables had a noteworthy impact on the model; 'Navan' produced negative significant results in five tests and 'mandible' produced four positive results.

Odds ratios for significant results demonstrate the strength of effect of abrasion and trampling in the models in which they were included. This measure of effect size relates to the degree of association between an independent and dependent variable (Morris and Gardner 1988). An odds ratio of 1 indicates that the presence/absence of the independent variable in the model has no effect on the dependent variable. Therefore the further the odds ratio is from 1, the greater the effect of the independent variable. The lower and higher figures for 95 % confidence intervals for the variable which had the greatest effect

Table 3 Summary of correlation results

Site	Specimens	% Abraded	% Trampled	Spearman	Sig.
All	29631	5.4	5.5	0.417	<0.001
East Chisenbury	611	3.1	4.1	0.344	<0.001
Eldon's Seat	1816	4.6	13.2	0.193	<0.001
La Sagesse	1181	4.0	6.0	0.760	0.009
Llanmaes	13487	3.3	2.7	0.100	<0.001
Navan Fort	1882	4.7	1.9	0.005	0.814
Potterne	6678	7.8	7.9	0.668	<0.001
Whitchurch	3706	10.5	9.5	0.650	<0.001

The significance value is shaded for tests which produced a statistically significant correlation between abrasion and trampling

(in every case abrasion or trampling) and the second greatest effect are presented in Table 6. The lower limit of the confidence interval is far higher than the next most important variable in every instance. All secondary variables have a lower confidence interval limit no higher than 3, except for Eldon's Seat in test R11 although this result produced an exceptionally wide-ranging confidence interval. Results from models indicate not only that abrasion is the most crucial variable in dictating trampling and vice versa, but also that no other variables pertaining to class of bone, archaeological context or modification come anywhere close to having a similar effect in any of the models.

Discussion

Results clearly demonstrate a strong correlation between trampling and abrasion, with six of the eight Spearman's correlation tests providing highly significant results. This provides compelling evidence that ungulate trampling is a major cause of abrasion in faunal assemblages. However, to be sure of this, further research is required to eliminate the effect of sediment character from responsibility for these patterns. Although, the general matrix character of these sites does not suggest that this variable can account for results, more thorough analysis is needed with the definition of the sediment in each context. This was beyond the scope of this research.

Trampling is clearly not always the principal cause of abrasion, as two sites showed no significant correlation. Whilst it is impossible to identify the aetiology of abrasion with confidence at these sites (as all other causes except for digestion leave no definable trace on bones), it is worthwhile assessing how they differ from the sites that produced strong positive correlations. The dataset suffers from an imbalance towards Late Bronze Age/Early Iron Age middens. Navan Fort and La Sagesse, the sites that do not show a significant

Table 4 Summary of binary logistic regression models

Test No.	Dep. Variable	Cases	Sig results	Steps	Sig variables									
R1	Abrasion	ALL	15	19	Trampling	Weathering	Caprine	Pig	Cattle	Ditch fill	Pelvis/Scapula	Mandible	Vertebra	Skull
					Neo/Juvenile	Llanmaes	Navan	Potterne	Whitchurch					
R2	Abrasion	10,000	9	24	Trampling	Weathering	Caprine	Pig	Pelvis/Scapula	Mandible	Navan	Potterne	Whitchurch	
R3	Abrasion	5,000	6	23	Trampling	Weathering	Caprine	Pig	Navan	Potterne				
R4	Abrasion	2,500	6	27	Trampling	Weathering	Long bone	Pig	Potterne	Whitchurch				
R5	Abrasion	1,250	2	27	Trampling	Long bone								
R6	Abrasion	625	1	19	Trampling									
R7	Abrasion	312	1	22	Trampling									
R8	Trampling	ALL	16	13	Abrasion	Weathering	Gnawing	Cattle	Midden	Shallow feat.	Pit fill	Small element	Mandible	Vertebra
					Skull	Neo/Juvenile	Navan	Potterne	Whitchurch	Eldon's Seat				
R9	Trampling	10,000	18	14	Abrasion	Weathering	Gnawing	Pig	Cattle	Midden	Shallow feat.	Pit fill	Ploughsoil	Pelvis/Scapula
					Small element	Long bone	Skull	Vertebra	Potterne	Eldon's Seat	Navan	MBA		
R10	Trampling	5,000	10	20	Abrasion	Gnawing	Caprine	Pig	Mandible	Long bone	Llanmaes	Navan	Potterne	Whitchurch
R11	Trampling	2,500	7	23	Abrasion	Caprine	Pig	Pelvis/Scapula	Mandible	Long bone	Eldon's Seat			
R12	Trampling	1,250	5	30	Abrasion	Weathering	Long bone	Llanmaes	Navan					
R13	Trampling	625	1	32	Abrasion									
R14	Trampling	312	2	31	Abrasion	Mandible								

Shaded categories have a positive effect on (increase) modification. All tests included 40 independent variables, comprising categories of modification, taxon, element, site, deposit type and phase

MBA Middle Bronze Age

Table 5 Summary of results from each regression series

Variable	Abrasion	Trampling
Trampling	7	NA
Abrasion	NA	7
Navan	3	−5
Weathering	4	3
Pig	4	−2
Mandible	−2	4
Potterne	4	2
Caprine	3	−2
Whitchurch	3	0
Gnawing	–	3
Eldon's Seat	–	3
Long bone	2	2
Cattle	1	2
Vertebra	−1	−2
Skull	−1	−2
Llanmaes	1	−2
Pelvis/scapula	2	0
Shallow feature	–	−2
Pit fill	–	−2
Small elements	–	−2
Neonatal/ juvenile	−1	−1
Ditch fill	1	–
Midden	–	−1
Ploughsoil	–	−1
Middle Bronze Age	–	1

Numbers indicate the number of significant results for each variable and whether the effect on the model is positive or negative (i.e., increases or decreases modification). *Dashes* indicate no significant results, whereas '0' indicates that significant results cancelled each other out (i.e., one positive and one negative). Variables that produced no significant results have been omitted

correlation, are the only assemblages in the dataset that are not middens of this type. The extensive taphonomic analysis that has been undertaken on middens demonstrated that the sites had undergone greatly contrasting taphonomic trajectories (Madgwick 2011) and therefore patterns do not indicate a correlation resulting from parallel depositional practices. In addition, analysis of La Sagesse shows a clear relationship between trampling and abrasion and results only narrowly fail to attain the stringent Bonferroni corrected *p* value. Therefore Navan Fort is the only site without evidence for a relationship. Navan Fort comprises few trampled specimens (1.9 % of specimens affected), thus making it far more difficult for significance to be attained in correlations. However, in a sample of almost 1,900 specimens, significance could certainly be attained if co-occurrence was common. As only two of 36 trampled specimens were also abraded, it seems likely that trampling was not the principal source of the modification at this site.

Regression models emphatically support the close link between the two modifications. Results demonstrate that each modification has a far greater effect on the prevalence of the other than any variable pertaining to site, phase, deposit type, taxon, element and modification in the model. Other perthotaxic modifications (sensu O'Connor 2008), which indicate sub-aerial exposure, also featured prominently in both series of models. Weathering produced four positive results in tests which had abrasion as the dependent variable and three when trampling was the focus. The importance of weathering is unsurprising if it is assumed that abrasion and trampling are closely linked, as certain modes of depositional treatment would have a similar effect on the three modifications. For example if butchery waste was frequently discarded in a midden amidst a settlement, bones would be susceptible to weathering and trampling, which could in turn cause abrasion.

Table 6 95 % confidence intervals for odds ratios for each of the models

	Principal variable	95 % CI for Exp (B)		Second variable	95 % CI for Exp (B)	
Test		Lower	Higher		Lower	Higher
R1	Trampling	18.295	24.520	Caprine	2.365	4.040
R2	Trampling	17.425	27.383	Weathering	2.182	3.385
R3	Trampling	17.678	34.192	Cervid	1.154	26.671
R4	Trampling	14.229	38.921	Weathering	3.150	7.962
R5	Trampling	14.387	65.366	Navan	1.512	8.532
R6	Trampling	9.006	77.242	NA	–	–
R7	Trampling	8.461	139.368	NA	–	–
R8	Abrasion	18.118	24.410	Eldon's Seat	2.537	4.114
R9	Abrasion	16.782	26.985	Eldon's Seat	2.469	4.972
R10	Abrasion	17.176	34.036	Long bone	3.242	10.453
R11	Abrasion	21.125	59.537	Eldon's Seat	11.241	182.941
R12	Abrasion	7.177	25.869	Long bone	1.900	5.908
R13	Abrasion	10.255	112.471	NA	–	–
R14	Abrasion	6.934	210.886	Mandible	2.390	33.041

Only the two variables that had the greatest effect on the model at the final stage of iteration are included

In addition some researchers have suggested that weathered bone is more susceptible to the effects of abrasion (Andrews 1995, p. 150; Behrensmeyer 1990; Fernández-Jalvo 1992), due to the loss of elasticity once the organic component degrades (Martill 1990). This view is supported by experimental research on fluvial abrasion undertaken by Fernández-Jalvo and Andrews (2003, p. 157). However, fluvial transport experiments by Thompson et al. (2011, p. 788) indicated that weathered material was least modified, although bone polishing was just one index in this research. The fact that all modifications result from sub-aerial exposure is considered the critical factor in the importance of weathering in models. Gnawing also had a noteworthy effect producing three positive results, but only in trampling tests. The effect of weathering and gnawing might have been more prominent in the models, except for the fact that both have a much more severe impact on a bone's surface. As a result, their co-occurrence can act to overprint and obscure the more subtle modifications of abrasion and especially trampling.

Categories of 'pig' and 'Potterne' also had a substantial impact on the abrasion model series, each producing four positive results. It was anticipated that site categories such as 'Potterne' may have a substantial effect, as site-specific depositional histories can engender particular modification patterns. In addition specific sedimentary matrices may be more conducive to abrasion and trampling. Blasco et al. (2008, p. 1613) noted that abrasion resulting from trampling most commonly occurred in sediments with a clayey matrix, with decimetre sized limestone clasts and Fernández-Jalvo and Andrews (2003, p. 157) stated that sedimentary abrasion (in terms of the rounding of fracture angles) occurs fastest in gravel matrices, followed by silts/clays, coarse sands and fine sands. Not all research is in agreement, but it is clear that site sedimentology affects both modifications.

The positive effect of 'pig' in the model is more difficult to explain. This may indicate that pig remains are inherently susceptible to abrasion. Further testing would be required to ascertain whether this is the case but research has indicated that pig bones are structurally different, being more porous than other domestic taxa (Robinson et al. 2003, pp. 397–398), a characteristic that could increase their susceptibility to modification. However, previous research on weathering indicated that pig remains were not significantly more commonly affected (Madgwick and Mulville 2012). In the trampling series, 'Navan' and 'mandible' were the only categories to produce at least four results, the site category producing five negative results and the element category four positive. It is difficult to ascertain whether the reduced trampling at Navan Fort results from specific modes of depositional practice (with bones being deposited away from thoroughfares) or the character of the site sedimentary matrix. It is plausible that the clay dominated strata could be more conducive to abrasion than trampling but further research is required to clarify this and sediment character is not the focus of this study. In any case, the strength of these patterns should not be over-emphasised, as odds ratios indicate that effect sizes are far smaller than for the principal variables of trampling and abrasion.

In some respects this research may appear circular, as it uses the relationship between the two modifications to identify the process of trampling through the modification of abrasion. This begs the question of why one would need to analyse abrasion, as trampling striations provide clearer evidence for the process. However, abrasion can still provide a key line of evidence for identifying trampling, as striations are notoriously difficult to identify (see Domínguez-Rodrigo et al. 2009) and are frequently overprinted by other modifications. By contrast abrasion is less susceptible to overprinting, as it tends to occupy a larger area of a bone's surface and is therefore less easily obscured by processes such as weathering and gnawing (although it remains vulnerable to the effects of acid erosion). Although striations are more likely to be obscured, if trampling has commonly occurred, modification would still be observable in a proportion of specimens in all but the very worst preserved assemblages. Therefore a correlation analysis can reveal whether there is a significant relationship between the two modifications at a site and this can determine whether abrasion can be used as a good indicator of the process of trampling. This is by no means a perfect scenario and it is not possible to determine that all examples of abrasion in an assemblage result from trampling. Different deposits may well have had contrasting depositional histories and therefore it may be necessary to test the correlation of modifications on different deposit types. Nonetheless this represents progress in enhancing the interpretative potential of a common modification that is rarely utilised due to its perceived diverse aetiology. The identification of trampling through an index other than only striations can facilitate considerably improved resolution on the depositional history and taphonomic trajectory of an assemblage by providing a more accurate representation of the prevalence and intensity of the process. This can in turn aid in establishing the potential of an assemblage for specific modes of study (e.g., spatial distribution of material, ^{14}C dating).

Whilst this study represents substantial progress in enhancing the interpretative potential of abrasion data, there are a number of caveats in the research. Although the dataset is relatively large it comprises material from only seven sites, several of which are contemporaneous. Similar testing is required on a broader range of sites, although later prehistoric middens provide an excellent case study due to their relatively high levels of modification. A further profitable extension to the research would be to target sampling at sites with sedimentary matrices of different character, as previous research is ambiguous as to the effect of this variable. This research is essential as it is clear that sediment character has some impact. A better understanding of the effect of sediment character will enable a more detailed assessment of how trampling data reflects the intensity of the process at sites with different geologies. Assessing this variable using the multivariate statistical approach employed in this study is problematic, as most sites have considerable diversity between contexts (see Table 2) and single contexts often include multiple identifiers (e.g., fine silty loam). Therefore establishing uniform, meaningful categories that suffer little from issues of inter-observer reliability would be very difficult.

Concluding remarks

Overall results clearly demonstrate the strength of the relationship between trampling and abrasion, but this is not the case at every site, as demonstrated by results for Navan Fort. Therefore correlation analysis is required at each site (or even deposit type) to establish whether or not trampling is the principal cause of the modification. Once this is undertaken, the validity of using abrasion data to identify the impact and intensity of trampling can be established.

Acknowledgments This study would not have been possible without the assistance of numerous museum staff that assisted with access to material, including Kay Ainsworth, David Allen, David Dawson, Jodie Deacon, Malcolm Fry, Adam Gwilt, Finbar McCormick, Lisa Webb and Peter Woodward. Data for this research was collected during an AHRC-funded PhD and I owe a debt of a gratitude to Jacqui Mulville who supervised the research. I am also very grateful to Jonathan Gillard for advice on statistical analysis, Clare Randall for guidance on Eldon's Seat matrix character and to Matt Law and two anonymous reviewers whose comments brought about considerable improvements to this paper.

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