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# 1 **The impact of sediment abrasion on tooth microwear analysis: an experimental study**

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## 20 21 **Abstract**

22  
23 Dental microwear analysis is a proxy for analysing the diet in extinct and extant vertebrates,  
24 especially mammals. The limits of these approaches are still rather poorly known, especially  
25 in terms of taphonomic impacts. Indeed, several physical or chemical phenomena may have  
26 altered the microscopic features linked to the diet and compromised their study. In this article,  
27 we evaluate the effect of sediment abrasion on teeth on low-magnification tooth wear studies.  
28 We used a tumbling machine in order to reproduce abrasion marks on 57 molars and  
29 premolars of *Equus* sp., *Capra hircus* and *Sus scrofa* employing two types of sediments: a  
30 mixture of clay and sand sediment with small (150-200 µm) and rounded particles and a  
31 sandy one with larger (350-500 µm) and sub-angular particles. The teeth underwent up to two  
32 hours of tumbling simulation and casts were made at regular intervals in order to evaluate the  
33 evolution of the taphonomic impact over time. Our experiment shows that 1) both sediments  
34 strongly alter the teeth after a certain time; 2) the fine particles contained in the mix of sand  
35 and clay sediment have a much stronger impact on the enamel than the sand; 3) the mix of  
36 clay and sand sediment tends to increase the number of pits and reduce the number of  
37 scratches, vice versa for the sand; 4) sedimentary and dietary marks do not have the same  
38 morphology and can be distinguished. The abrasion marks (compared to dietary scratches)  
39 tend to be wider, shorter, with an isotropic distribution, more frequent on the most exposed  
40 parts of the teeth (such as the cusps or the edges). The pits resulting from sediment tumbling  
41 present an irregular morphology in comparison with dietary pits, which are rounder. Both  
42 sediments have an impact on the enamel surfaces. Thus, when signs of taphonomic alteration  
43 (e.g. presence of abrasion marks, taphonomic pits, notches in the edges of enamel) are  
44 documented, we recommend avoiding studying the tips of the cups of the Suidae (and  
45 probably other bunodont teeth) and the portions of enamel at the edge of equid teeth which  
46 are more affected by taphonomic processes, especially in the mix of sand and clay sediment.  
47 This work has important implications for microwear studies applied to fossil samples. It  
48 makes it possible to recognise some taphonomic features linked to mechanical abrasion of the  
49 enamel, to consider with more caution the teeth that have been preserved in fine sediment, and  
50 to choose, in order to characterise the diet, the areas least impacted by taphonomic alterations.

## 51 52 **Keywords:**

54 Tooth wear; Taphonomy; Tumbling; Sequential experimentation; mechanical alteration

55

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57

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68

## 69 **Conflicts of interest/Competing interests**

70 None

71

## 72 **Availability of data and material**

73 All raw data are sent with this manuscript

74

## 75 **Code availability**

76 Not applicable

77

## 78 **Authors' contributions**

79 Antigone Uzunidis: conception of the work; acquisition, analysis and interpretation of the  
80 data; writing of the manuscript

81 Antonio Pineda: conception of the work; analysis and interpretation of the data; writing and  
82 revision of the manuscript

83 Sergio Jiménez-Manchón: conception of the work; acquisition, analysis, and interpretation of  
84 the data; revision of the manuscript

85 Alexandros Xafis: analysis of the data; revision of the manuscript

86 Vincent Ollivier: acquisition of the data

87 Florent Rivals: conception of the work; acquisition, analysis and interpretation of the data;  
88 writing and revision of the manuscript

89

90

## 91 **1. Introduction**

92

93 For a long time, many works have been dedicated to reconstructing ecological parameters,  
94 and in particular the diet of fossil taxa. Many proxies have been developed for this purpose,  
95 such as the shape analysis of the maxilla (e.g. Solounias et al. 1988; Solounias and Moelleken,  
96 1993a; Solounias and Moelleken 1993b), the study of the of the hypsodonty index of the teeth  
97 (e.g. Fortelius 1985; Janis 1988; 1995; Mendoza et al. 2002), tooth mesowear (Fortelius and  
98 Solounias 2000) and dental microwear, both stereomicroscopic analysis (Walker et al. 1978;  
99 Solounias and Hayek 1993; Solounias and Semprebon 2002; Semprebon et al. 2004a) and  
100 dental microwear texture analysis (Calandra and Merceron 2016; Scott et al. 2006). Dental  
101 microwear is an approach with a high temporal resolution which allows the characterisation of  
102 an individual's diet on a short temporal scale corresponding to the time of death (Grine, 1986;  
103 Davis and Pineda Munoz 2016; Sánchez-Hernández et al. 2016). The other methods

104 correspond rather to a longer temporal scale, the morphology-based ones reflecting the  
105 evolutionary trend of a lineage and of the tooth mesowear, the animal life-time tendency  
106 (Ackermans et al. 2020).

107 The first studies of dental microwear date back to the 1950s when Butler (1952) and Mills  
108 (1955) noticed that the orientation of the scratches observed on the wear facets of the tooth  
109 enamel could reflect the directions of movement of the jaws and, most probably, the diet. In  
110 1959, Baker and colleagues correlated tooth wear in sheep populations with diet and the  
111 composition of quartz-rich soils. Subsequently, new evidence of the abrasive action of  
112 phytoliths was revealed by their discovery at the end of scratches on the surface of human  
113 tooth enamel (Fox et al. 1994 1996). Dental microwear is, since Grine (1977), widely used to  
114 study the palaeodietary flexibility of wild taxa (e.g. Teaford 1988; Semprebon and Rivals  
115 2007) and to reconstruct the habitats in which herbivores lived (e.g. Semprebon et al. 2004a,  
116 2004b; Merceron et al. 2004; Rivals 2012). To a lesser extent, this tool has also been used to  
117 analyse the palaeodiet in domestic animals in order to better understand the management  
118 strategies employed by herders/farmers and landscape use (e.g. Mainland 2003, 2006; Gallego  
119 et al. 2017; Jiménez-Manchón et al. 2019).

120 Dental microwear studies refer to several techniques of analysis: scanning electron  
121 microscopy (e.g. Walker et al. 1978), microwear texture analysis (Scott et al. 2005), and low-  
122 magnification microwear analysis (Solounias and Semprebon 2002; Semprebon et al. 2004).  
123 Although these techniques are widely used, their limitations are still rather poorly defined.  
124 Various authors have highlighted problems concerning inconsistencies in the teeth or facets  
125 selected (Krueger et al. 2008; Ungar et al. 2010; Xafis et al. 2017), variations in moulding and  
126 casting methods (Galbany et al. 2006; Williams and Doyle 2010; Mihlbachler et al. 2019), or  
127 inter-observer variability (e.g. Mihlbachler et al. 2012). Among the possible biases for  
128 defining an individual's diet from tooth wear, taphonomic problems are largely  
129 underestimated and poorly investigated. Although teeth are often much better preserved than  
130 bones (Lyman 1994), chemical or physical alterations can destroy or alter diet-related  
131 information (King et al. 1999; El-Zaatari 2010; Dauphin et al. 2018; Böhm et al. 2019; Weber  
132 et al. 2020).

133 So far, very few experiments have tested the effects of tumbling on tooth enamel. Those  
134 experiments were designed to mimic the effect of sediment abrasion (Gaudzinski-Windheuser  
135 et al. 2010). Gordon (1983, 1984) tumbled human teeth in four types of sediment (dry  
136 sediment and in aqueous mixtures of these sediments) and showed that tumbling only seems  
137 to erase feeding features (scratches and pits) rather than adding new ones. King and  
138 colleagues (1999) carried out the same type of experiment on human teeth and with three  
139 types of sediment (quartz pebbles, particles size: 2,000–11,000  $\mu\text{m}$ ; coarse sand, particles  
140 size: 500–1,000  $\mu\text{m}$ ; medium sand, particles size: 250 and 500  $\mu\text{m}$ ). This experiment showed  
141 similar results to that of Gordon (1984) - tumbling would remove the traces and not add to  
142 them. Puech and colleagues (1985) tested the impact of projection and friction of sand grains  
143 (between 50 and 200  $\mu\text{m}$ ) on human tooth surfaces. This experiment allows the authors to  
144 describe specific marks related to the diet which can be partially or completely erased due to  
145 taphonomic alterations. Thus, when taphonomic alterations are observed on the teeth, several  
146 authors indicate that chemical and physical alterations can be differentiated from the  
147 preserved areas to avoid discarding specimens and reducing the sample size (Puech et al.  
148 1985; Teaford 1988; King et al. 1999; Martínez and Pérez-Pérez 2004).

149 For now, only one experimentation has been conducted on non-human mammal teeth (Böhm  
150 et al. 2019). This experiment sought to evaluate the impact of tumbling on studies based on  
151 microwear texture analysis using confocal microscopy. The impact of three types of sediment  
152 (fine sand: particles size: 51–168  $\mu\text{m}$ ; fine sand particles size: 112–292  $\mu\text{m}$ ; medium sand:  
153 particles size: 221–513  $\mu\text{m}$ ) on the teeth of three different taxa (*Equus* sp., *Capreolus*

154 *capreolus* and *Otomys* sp.) was tested. This study showed that some parameters were strongly  
155 affected by tumbling and others were not and that the results depend on the taxon and the  
156 sediment. *Otomys* sp. teeth were hardly affected by tumbling and the differences between  
157 browsers and grazers among large mammals still persisted after tumbling.

158 Low-magnification microwear analysis involves direct observation through a  
159 stereomicroscope at 35x of the micro-features (pits and scratches) caused by food and grit  
160 particles on the occlusal surface of dental enamel. Compared to microwear texture analysis,  
161 this method allows a direct observation of the sample by the observer. Although this is often  
162 considered a limitation due to interobserver bias (e.g. DeSantis et al. 2013; Mihlbachler et al.  
163 2012), it also offers the possibility of distinguishing taphonomic (abrasion marks) and non-  
164 taphonomic (dietary) traces on the basis of their morphology as it is commonly applied to the  
165 study of bones (e.g. Behrensmeyer et al. 1986).

166 In this study, our goal is to establish the impact of tumbling on the teeth of several ungulate  
167 taxa, depending on the type of sediment. Tumbling experiments were already used in several  
168 taphonomic studies in order to mimic the effect of water abrasion on faunal remains (e.g.  
169 Gaudzinski-Windheuser et al. 2010; Pineda et al. 2019). Pits and scratches are the main  
170 features studied in dental microwear studies. The abrasion marks and pits that originated  
171 during the tumbling process were identified, characterised, and compared to the traces  
172 resulting from the diet. For that purpose, we selected three taxa according to their dental  
173 morphology: hypsodont teeth with thick enamel (*Equus* sp., enamel thickness: 1.5-2 mm,  
174 Kozawa et al. 1988), hypsodont teeth with thin enamel (*Capra hircus*, enamel thickness: 0.53  
175 mm, Grine et al. 1987), and brachydont teeth (*Sus scrofa*). The teeth were separated into four  
176 groups, two of which were tumbled with a Miocene sand rich in quartz and the other two with  
177 a mix of sand and clay sediment. The abrasion was simulated with a tumbling machine in  
178 which they spent a total of two hours. At regular intervals, the teeth were moulded in order to  
179 follow the evolution of the taphonomic alterations over time. We hypothesised that Miocene  
180 sand would have a greater effect on the enamel due to its abrasive properties, compared to the  
181 mixed one (Rozada et al. 2018). Also, we expected a difference between taxa, i.e. that equid  
182 teeth would be more resistant to alterations due to their thicker enamel. Comparison of these  
183 features with non-taphonomic ones would help to avoid bias and improve dental microwear  
184 studies.

185

## 186 **2. Material and methods**

187

### 188 2.1 Sediments

189

190 Two types of sediment were selected because of their composition in order to evaluate the  
191 significance of their possible impact. The sediments were not sieved for the experiment in  
192 order to compare the effects of sediments that can be found on teeth from archaeological sites.  
193 We therefore chose sediments with opposite characteristics: Miocene sand and a mixed  
194 sediment with clay and sand. The particles that make up the Miocene sand are larger and sub-  
195 angular, those that make up the mix of sand and clay sediment are smaller and rounder. The  
196 determination of the size of the grains was carried out by sieving that was limited to the  
197 extraction of the sedimentary matrix (mesh 250 µm) and measurements were carried out  
198 directly on the grains themselves via dinolite software (measurements of axes). The angularity  
199 of the grains was qualitatively determined: the sub-angular grains have sharp or right-angled  
200 edges while the rounded grains have no edges.

201

202 The Miocene sand comes from La Motte d'Aigues (Vaucluse, France). This sediment is  
203 composed of medium to fine grains and is rich in translucent sub-angular quartz (60% of the

204 sediment) and blunt to rolled green quartz (30% of the sediment). The particles are quite large  
205 in size (350-500  $\mu\text{m}$ ).

206 The mixed clay-sand sediment comes from a cave in the town of La Bouilladisse (Bouches-  
207 du-Rhône, France), dug into Jurassic limestone. The sediment is sandy-silty to gravelly,  
208 mainly composed of relatively heterogeneous limestone and quartz elements. The quartz  
209 particles are quite small in size (150-200  $\mu\text{m}$ ), several varieties can be observed (pink quartz  
210 and white quartz), all are blunt. Limestone ceiling elements are visible (heterometric and sub-  
211 angular), as well as some fragments of white calcitic and conglomerate cements. Aeolian  
212 feldspar (pink to almost red), with the quartz, represents about 20% of the observed fractions.

213

## 214 2.2 Experimental protocol

215

216 Teeth from extant animals were selected for this experiment. Taxa used for the purpose of this  
217 study included equids (*Equus* sp), goats (*Capra hircus*) and wild boars (*Sus scrofa*). Teeth  
218 were separated into four groups: Group 1 included two equid teeth and 10 goat teeth; Group 2  
219 was composed of 15 wild boar teeth; Group 3 included three equids and nine goat teeth; and,  
220 finally, Group 4 was composed of fourteen teeth belonging to wild boars. The teeth were  
221 separated in order to limit tooth-to-tooth impacts between them during the experiment and to  
222 facilitate their distribution and study afterwards. Groups and variables included in each one of  
223 them are summarised in **Table 1**.

224

225 All the teeth were subjected to the abrasion process in a tumbling machine (KT-3010 SUPER-  
226 TUMBLER, size: 300x240 mm) located at the *Catalan Institute of Human Paleoecology and*  
227 *Social Evolution* (IPHES) in Tarragona. Groups 1 and 2 were exposed to the mix of sand and  
228 clay sediment mixed with water (mix sand-clay: 60%, water: 40%, 2 kg in total) whereas  
229 Groups 3 and 4 were exposed to the sand sediment mixed with water (sand: 60%; water: 40%,  
230 2 kg in total). The time of exposition was the same for all four groups. Six cumulative cycles  
231 of exposure to tumbling were reproduced: cycle 1 (2'), cycle 2 (3'), cycle 3 (10'), cycle 4 (15'),  
232 cycle 5 (30') and cycle 6 (60'). The total time at the end of the experimentation was two hours.  
233 The tumbling machine was set to 83.3 revolutions per minute (i.e. 5000 revolutions per hour)  
234 and the rotations were uninterrupted and unidirectional in each cycle.

235 Moulds of the occlusal surface were produced before the beginning of the experiment and  
236 after each cycle. Before moulding, the occlusal surface of each tooth was cleaned using  
237 acetone and then 96% ethanol. Then the surface was moulded with a high-resolution silicone  
238 (vinylpolysiloxane; Provil novo light, regular set) and casts were made using clear epoxy  
239 resin (EPO 150). The transparent casts were then observed with a stereomicroscope at  
240 magnifications of  $\times 35$  and microphotographs were taken using a SMZ1500 stereomicroscope  
241 (AU), Zeiss Stemi 2000C (FR), Leica MZ16 (SJM), Leica MZ12 stereomicroscope and Leica  
242 CLS 100 oblique lighting source (AX). Observations were restricted to a standard surface of  
243  $0.16 \text{ mm}^2$  (using an ocular reticule). The variables chosen to observe and quantify are those  
244 established by Solounias and Semprebon (2002) and Semprebon et al (2004a), which are  
245 traditionally used in a large number of studies (e.g. Xafis et al. 2017; Rivals et al. 2017; 2019;  
246 Uzunidis 2020): pits (small and large), scratches (fine, coarse and hypercoarse), cross  
247 scratches and gouges. These features were quantified on the protoconid and/or metaconid on  
248 the lower teeth and the paracone and/or metacone on the upper teeth. The variable "cross  
249 scratches" has not been recorded for the suids because, due to the conformation of their teeth  
250 (bunodonts), the scratches are always crossed. It is therefore not possible to observe a  
251 preferential orientation to which to refer to count the exact number of cross scratches. The  
252 same area was observed on the subsequent moulds of the same tooth (with the previous-  
253 experiment mould) through the six cycles of the experiment. We used reference features on

254 the surface, such as obvious pits or scratches or the topography of the surface, to locate the  
255 reticule precisely at the same place on the successive casts.  
256 The four different groups were analysed by different observers. All observers have previous  
257 experience in dental microwear analysis, although one of them (FR) is more experienced than  
258 the others (AU, SJM and AX). Group 1 was analysed by SJM, Group 2 by FR, group 3 by  
259 AU, group 4 by AX.

### 260 2.3 Morphometrical study of the taphonomic alterations

261  
262  
263 In order to characterise abrasion marks compared to dietary micro-features we have selected  
264 and described the evolution of a sample of six teeth. These teeth belong to the three taxa  
265 studied (wild boar, goat, and equid), taking into account the two types of sediments used (mix  
266 of sand and clay and sand). The teeth were randomly selected but they are representative of  
267 the wear pattern for the group in question. The specific elements studied are:

- 268 - 1: Tooth #II.1. Right M3 of *Sus scrofa* exposed to tumbling in the mix of sand and  
269 clay sediment.
- 270 - 2: Tooth # IV. 8. Right M1 of *Sus scrofa* exposed to tumbling in sands.
- 271 - 3: Tooth #I.6. Right M2 of *Capra hircus* exposed to tumbling in the mix of sand and  
272 clay sediment.
- 273 - 4: Tooth #III. 10. Right M1 of *Capra hircus* exposed to tumbling in sands.
- 274 - 5: Tooth #I.7. Right PM4 of *Equus* sp. exposed to tumbling in the mix of sand and  
275 clay sediment.
- 276 - 6: Tooth #III.6. Left M1 of *Equus* sp. exposed to tumbling in sands.

277  
278 The weathering stage of these remains was established according to Behrensmeyer's (1978)  
279 stages. The occlusal surfaces of the teeth were observed and described (see supplementary  
280 data 2). The nomenclature used to describe the alterations closely resembles the terms used  
281 for dental microwear. To avoid misunderstandings, the term "abrasion marks" will be used for  
282 scratches of taphonomic origin produced in the tumbling machine, while the term "scratch"  
283 will refer exclusively to dietary features. For other features, we will use the adjective  
284 "taphonomic" when necessary (e.g. "taphonomic pit").

### 285 2.4 Statistical analysis

286  
287  
288 In order to fully understand the changes in each of the variables considered as a function of  
289 the time spent in the tumbling machine, we used two statistical analyses: principal component  
290 analyses (PCA) and the Friedman test.

291 The PCA allowed us to observe how each of the variables changed over the cycles, and the  
292 Friedman test allowed us to determine whether any differences were significant ( $p = 0.95$ ).  
293 The minimum number of individuals per sample to perform those statistical analyses is five.  
294 Both were realised using the software Xlstat v. 2014.5.03. The principal component analysis  
295 was built thanks to the Spearman rank correlation coefficient, which is recommended for  
296 small datasets (Vásquez-Correa and Laniado Rodas 2019). Friedman's ANOVA is a non-  
297 parametric test which allows testing if paired samples come from the same population or from  
298 populations with identical properties. It can be applied to small samples and is more likely to  
299 be dependent on the nature of sample variances, so it allows a parsimonious interpretation of  
300 the data (Rigdon 1999). In order to artificially increase the number of samples and to reduce  
301 the errors due to the small size of the sample we used the Monte-Carlo method and simulated  
302 the distribution of the variables 10,000 times.

303

### 3. Results

#### 3.1 *Capra hircus* in the mix of sand and clay sediment.

From the ten teeth available at the beginning (**Tab. 1**), one was immediately (after 0 min) discarded because of its alteration, probably in relation to a health issue with the animal, and only two samples (belonging to other animals) were suitable for microwear analysis one hour later, and none two hours later. Because of the experiment, the “non-suitable teeth” showed enamel surface alterations that were too pronounced to recognize dental wear parameters (e.g. pit, scratches, gouges) used in the reconstitution of the diet. The statistical analyses will focus on a tumbling period between 0 and 30 minutes where sufficient teeth, five, are available (**Tab. 2**). The number of pits, coarse scratches and cross scratches remains very similar, from 0 to two minutes (**Fig. 1**). However, the number of coarse scratches and cross scratches increases a little between two and five minutes of tumbling, as do the number of large pits after 30 minutes. The number of gouges never changes, regardless of the time spent in the tumbling machine, and always remains equal to zero. The differences between the different cycles are still statistically insignificant in every variable (cf. supplementary data 1).

#### 3.2 *Equus* sp. in the mix of sand and clay sediment.

Only two teeth were available to study the impact of tumbling on *Equus* enamel surfaces (**Tab. 1**). No statistical tests were carried out due to the small number of teeth. On the two teeth (**Tab. 3**), quantification of tooth microwear was possible up to 30 minutes of tumbling for the first one (tooth # I.1), and one hour for the second (tooth # I.7). The comparison of the evolution of the variables from the beginning to 30 or 60 minutes of tumbling (according to the teeth) shows that the friction of the mix of sand and clay sediment against the enamel seems to increase the number of small and large pits and erases the fine scratches. These alterations remain quite limited since there is a maximum of seven extra pits in one case and five fine scratches erased in another.

#### 3.3 *Sus scrofa* in the mix of sand and clay sediment.

From the fifteen teeth available at the beginning (**Tab. 1**), five were not suitable for the experiment (cf 3.1) and only two still preserved microwear features after one hour of tumbling and none after two hours. The statistical analyses will focus on the samples from the period from the beginning to 15 minutes of tumbling, where sufficient sample size is available. The other features we quantified increase regularly through time (**Fig. 1**). While the microwear patterns remain similar between the start and two minutes of tumbling, the number of fine and coarse scratches, small and large pits increases between five and 10 minutes of tumbling. The differences between the cycles are very small and never statistically significant except for the number of small pits between the beginning and five minutes of experiment ( $p= 0.0267$ ) (cf. supplementary data 1). This variable increases from a mean of 7.33 pits at cycle 0 to 9.17 pits at cycle 3 (**Tab. 4**).

#### 3.4 *Capra hircus* in sand sediment.

From the nine teeth available at the start (**Tab. 1**), five were observable after two hours, which allows statistical analyses on every cycle (**Tab. 2**). The number of coarse and hyper coarse scratches never changes regardless of the time spent in the tumbling machine and always



354 remains equal to zero. On the first axis (43.24% of the variance) the teeth that were tumbled  
355 for up to 30 minutes remained quite similar, while the number of gouges and cross scratches  
356 increased after one and two hours of experiment (**Fig. 2**). Nevertheless, the differences  
357 between the different cycles are still statistically insignificant in every variable (cf.  
358 supplementary data 1).

359

360 3.5 *Equus* sp. in sand sediment.

361

362 Only three teeth were available at the beginning of the experiment (**Tab. 1**). No statistical  
363 tests were carried out due to the small number of teeth. For all the teeth (**Tab. 3**), the  
364 observations were possible up to two hours of experiment. On two teeth (teeth # III.1 and  
365 III.6), the number of small pits decreased and the number of fine scratches increased. On the  
366 last one (tooth # III.2), the number of fine scratches remained mostly the same while the  
367 number of small pits increased. These alterations remained quite limited since there was a  
368 maximum of six extra pits, 10 erased small pits, and up to seven fine scratches added and five  
369 erased.

370

371 3.6 *Sus scrofa* in sand sediment.

372

373 From the fourteen teeth available at the start (**Tab. 1**), one was discarded at the beginning of  
374 the experiment (cf. 3.2) and eight were suitable two hours later, which allows statistical  
375 analyses on every cycle. The teeth from the beginning, and two minutes later, remained quite  
376 similar, while the number of gouges, coarse scratches and large pits increased from five  
377 minutes of tumbling up to two hours (**Fig. 2**). The differences between the cycles are very  
378 small and never statistically significant except for the number of coarse scratches between the  
379 beginning (mean = 4.38) and 10 minutes of tumbling (mean = 6.88) ( $p = 0.0204$ ), and the  
380 beginning and two hours of tumbling (mean = 7.13) ( $p = 0.0093$ ), which increased during the  
381 experiment (**Tab. 4**). It is also significant for the number of small pits between the beginning  
382 (mean = 20.75) and 10 minutes of tumbling (mean = 15.13) ( $p = 0.0040$ ), and the beginning  
383 and one hour of tumbling (mean = 15.88) ( $p = 0.0169$ ), which decreased during the experiment  
384 (cf. supplementary data 1).

385

386 In groups 1 and 2, after one hour of tumbling, one out of two equid teeth is observable and  
387 only 22.2% of the *S. scrofa* and 25% of the *C. hircus*. After two hours, the surface of all the  
388 teeth regardless of the species was too badly altered and none of them could be studied. For  
389 the sandy sediment, after one and two hours of experimentation, the three equid teeth were  
390 still observable, about 60% of the suid teeth (cycle 5: 69.23%, cycle 6: 61.53%), and 55.55%  
391 (for the two cycles) of the caprid teeth.

392

393 3.7 Morphological description of the occlusal surface of the six selected teeth

394

395 During the observation, it has been possible to document that the main problem when carrying  
396 out microwear analyses on teeth affected by tumbling processes is that this process may have  
397 altered or erased the dietary microwear features. Since dietary inferences are made from  
398 quantification of these scratches and pits, their partial or total disappearance can lead to  
399 erroneous dietary interpretations. For this reason, we have proceeded to describe the moment  
400 in which the number of microwear scratches or pits differs from the original, as well as to  
401 identify criteria that allow the identification of abrasion marks.

402 After the microscopic analysis, two trends have been observed (see supplementary material  
403 2): 1) appearance of abrasion marks produced during tumbling; 2) disappearance of  
404 microwear scratches and pits as a result of tooth enamel abrasion after tumbling.

405 Regarding the first point the appearance of new abrasion marks and taphonomic pits it is  
406 noteworthy that they are more likely to be distinguishable from dietary microwear scratches in  
407 all phases of the observation (**Fig. 3**). The abrasion marks tend to be wider, shorter, with a  
408 chaotic random distribution, being more frequent on the most exposed parts of the teeth (such  
409 as the cusps or the edges) and producing changes in the texture of the enamel. The  
410 taphonomic pits present an irregular morphology and changes in relation to the enamel texture  
411 (**Fig. 3**). Regarding the second point, relative to the disappearance of microwear scratches and  
412 pits, we can determine that it is a consequence of the abrasion or erosion produced by the  
413 sedimentary particles.

414 This evidence appeared earlier in the case of wild boar and goat (during cycle 2), while in the  
415 case of equids these can be documented up to cycle 4.

416 According to the type of sediment, in the case of wild boar and equids, the mix of sand and  
417 clay sediment produced more abrasion marks and taphonomic pits than sand. The mix of sand  
418 and clay sediment began to obliterate the microwear pattern after five minutes (wild boar) and  
419 30 minutes (equid), while the sands did so after 15 minutes and 60 minutes respectively. In  
420 the case of the goat the two sediments erased the microwear features starting at 30 minutes in  
421 both sedimentary contexts. Polishing the enamel surface implied the progressive  
422 disappearance of at least part of the scratches. It has been observed that polishing appeared at  
423 different times in the case of equid and boar teeth. In the case of wild boar, the tips of the  
424 cusps are the first place where abrasion is documented, while at the base of the cusps there are  
425 no signs of alteration. In the case of the equid, the abrasion appears first at the edges of the  
426 tooth, while the enamel in the middle of the occlusal surface remains unaltered. This does not  
427 occur in the case of the goat, probably as a consequence of the specific morphology of  
428 selenodont teeth.

429

#### 430 **4. Discussion**

##### 431 4.1 Differences between sand and the mix of sand and clay sediments.

432

433 Taphonomic analysis revealed a tendency towards an increase in the numbers of abrasion  
434 marks, taphonomic pits and gouges over time, both in sands and in the mix of sand and clay  
435 sediment. Some previous experimental work on bone tumbling had determined that the  
436 creation of striae is a consequence of the abrasion process, regardless of the content of the  
437 sedimentary matrix employed (Behrensmeyer et al. 1986; Domínguez-Rodrigo et al. 2009,  
438 2017; Gaudzinski-Windheuser et al. 2010; Rabinovich et al. 2012; Pineda et al. 2019). In fact,  
439 the first works of Behrensmeyer established that abrasion is caused by the sedimentary  
440 particles in suspension (Behrensmeyer et al. 1986). These works had not analysed the impact  
441 of this process on teeth; however, our results suggest that it also occurs on teeth in a similar  
442 form.

443 The appearance of these new features (abrasion marks, taphonomic pits) is exponential to the  
444 time of exposure of the materials to the experimental process. However, a difference in  
445 relation to the types of sediment used was detected: while in the mix of sand and clay  
446 sediment most abrasion marks, taphonomic pits and gouges appear in intermediate cycles (2  
447 and 3, which imply a maximum of 15 minutes of abrasion), in the case of sands, a notable  
448 increase is detected from more advanced cycles (more than 30 minutes of exposure). This fits  
449 with the observations made by Fernández-Jalvo and Andrews (2003), which suggested that  
450 sands have a high abrasive power when experimental processes of abrasion are conducted.  
451 Through these observations, in our experiment the sand sediment was expected to be more

452 abrasive than the mix of sand and clay sediment due to the abundant presence of sub-angular  
453 quartz particles (60% of the sediment). In the mix of sand and clay sediment, the quartz grains  
454 were scarcer (20% of the sediment) and blunt.

455 Miocene sand particles are larger (350-500  $\mu\text{m}$ ) than the ones in the mixed sand and clay  
456 sediment (150-200  $\mu\text{m}$ ). As we used the same weight of sediment in the tumbling machine,  
457 this means that more particles were present in the mixture of sand and clay sediment. It is  
458 possible that the abrasion potential of each particle has a lower impact than the number of  
459 times a particle comes into contact with the enamel. Since more grains are present in the mix  
460 of sand and clay sediment, the probability of impacting the enamel is higher than in the sandy  
461 sediment, which contains fewer particles. In their experiment, King et al. (1999) also observed  
462 that the “smallest particles caused the most damage to microwear features and enamel” (p.  
463 367).

464 On the other hand, in some cases we have documented a decrease in scratches and pits. This  
465 phenomenon occurs in the fine scratches documented in equid teeth subjected to tumbling  
466 with the mix of sand and clay sediment and pitting in equid and wild boar teeth in sands.  
467 Previous experimental research focused on the effect of the abrasion processes on  
468 anthropogenic (cut marks) and natural (abrasion marks) modification has shown the power of  
469 this process to alter and obliterate bone surface modifications (Shipman and Rose 1983;  
470 Behrensmeyer et al. 1989; Gaudzinski-Windheuser et al. 2010; Rabinovich et al. 2012; Pineda  
471 et al. 2019). After a prolonged exposure of the materials to tumbling (more than one hour) the  
472 main characteristic is the total or almost total disappearance of scratches and pits from the  
473 enamel surfaces in both types of sediment (**Tab. 5; Fig. 4**) In the case of microwear analysis,  
474 the enamel surfaces of the teeth were too altered by the experiment (often after one hour of  
475 tumbling) and the original microwear pattern was completely unreadable. The dietary  
476 microfeatures were completely erased and replaced by abrasion marks. In a regular dietary  
477 microwear study, these teeth would have been discarded. For the teeth that still preserve some  
478 original (dietary) microwear pattern, the identification of features of taphonomic origin is  
479 necessary to recognize enamel areas that are suitable for microwear analysis and to produce  
480 reliable and accurate results.

481 Tumbling experiments on bones with more or less quartz-rich sediment show that the mix of  
482 sand and clay sediment has a similar impact to sandy sediment (Rozada et al. 2018). Several  
483 leads can explain the importance of the impact of the mix of sand and clay sediment  
484 compared to sand sediment, but this issue needs to be more carefully examined and other  
485 types of sediment need to be considered with a larger sample of teeth.

486 Before the microwear pattern was completely erased, we were able to observe that the friction  
487 of the sediment against the enamel slightly altered the diet-related features. For all the species,  
488 the mix of sand and clay sediment appears to increase the number of pits and reduce the  
489 number of scratches while the sand appears to have the opposite effect. However, those  
490 impacts are minimal and never significant except in some cases for *Sus scrofa* (cf. *infra*). This  
491 experiment highlights the different impact on the teeth depending on the sediment. Studies  
492 conducted on archaeological and paleontological material should be more cautious and look  
493 out for taphonomic alterations, especially when the sediment is fine (like in the mix of sand  
494 and clay sediment).

495

#### 496 4.2 Differences between *Equus* sp., *Capra hircus* and *Sus scrofa*

497

498 A larger proportion of equid teeth than those of goats or wild boars can be studied in cycles 5  
499 or 6 in the two types of sediments i.e. after 60 to 120 minutes of tumbling (**Tab. 5**). This  
500 could be due to the different morphology of the teeth. Equid teeth, being larger, elongated,  
501 and heavier than those of wild boar or goat, must roll in the tumbler on their lateral faces (of

502 the crown of the tooth) and have little impact with the occlusal surface (which we have  
503 observed). On the contrary, the teeth of wild boar or goat, being smaller and lighter, must  
504 have had a similar impact on all their faces. It could also suggest that equid enamel is stronger  
505 than the other two species. The hardness of enamel depends on its mineral density, which  
506 permits its resistance to abrasion (Waters 1980). This property also makes it more fragile and  
507 easily breakable, especially at the interface of the crystallites that compose it (Waters 1980;  
508 Currey 1999). Our experiment did not result in macroscopic fractures but in an intensive  
509 abrasion of the occlusal surface. Previous works already underlined the hardness of equid  
510 enamel because of its adaption to grazing a large amount of low-quality fodder, which leads  
511 to high abrasion patterns (Janis 1976), although the hardness of the enamel in horses seems to  
512 vary between domestic breeds and increases with increasing age (Muyllé et al. 1999). We  
513 could not find any direct data evaluating the hardness of *Capra* enamel, but it is probably less  
514 hard than that of horses (Popowics and Herring 2006). Studies have shown that the enamel of  
515 Suidae is weak, especially compared to humans (Popowics et al. 2004; Popowics and Herring  
516 2006). This property allows suid teeth to remove the tip of the tooth and preserve what  
517 remains, which would improve the durability of the crown for a varied diet (Popowics *op. cit.*;  
518 Popowics and Herring *op. cit.*). However, in our study, we only considered very slightly worn  
519 suid teeth with intact cusp tips. Thus, we considered the most fragile portions of the suid  
520 teeth.

521 We have only included a few equid teeth for comparison but these preliminary observations  
522 would indicate that the strength of their enamel preserves them better than other species from  
523 alterations due to tumbling. Goat teeth are more fragile. It is likely that this is also due to the  
524 thinner enamel of the buccal and lingual walls compared to those of equids. Nevertheless, as  
525 long as the enamel remained in good enough condition to allow microscopic observation, the  
526 variations observed between cycles were always minimal and not significant. Due to the  
527 'rounded' shape of the wild boar teeth, i.e. brachydont and bunodont teeth, they tumble on all  
528 surfaces. Equid and goat teeth are hypsodont and their elongated shape probably tumbled  
529 around their main axis, and the contact with the sediment affected the tooth crown more than  
530 the occlusal surface. In wild boar the tips of the cusps were altered before the deeper 'valleys'  
531 in between the cusps (more protected areas). In equid and goat teeth, the tumbling affected the  
532 crown, and not so much the occlusal surface. For the equids, the edges of the surface at the  
533 limit with the crown are impacted by the tumbling, while for the goat the potential alterations  
534 on the occlusal surface are rather homogenous, probably due to the smaller occlusal surface of  
535 the teeth.

536

#### 537 4.3 Effect of taphonomic processes on microwear studies

538

539 The observation of qualitative microscopic features on the sample of six selected teeth  
540 highlights two trends: 1) the appearance of abrasion marks and pits produced during tumbling;  
541 2) the disappearance of microwear scratches and pits as a result of tooth enamel abrasion from  
542 tumbling; 3) the appearance of polished surfaces, in some cases, at the tip of the cusps in wild  
543 boar teeth and at the edges of the occlusal surface in equid teeth.

544 The effects of abrasion include changes in the texture of the enamel, loss of tissue (mostly  
545 inferred though documentation of notches on the edges of the teeth) and changes in the  
546 surface of the teeth, including the appearance of new striae and the obliteration of dietary-  
547 related ones.

548 Microscopically, more abrasion marks and taphonomic pits are likely to be distinguished from  
549 those produced by diet, one reason why its identification is not a problem for microwear  
550 studies (Teaford 1988; King et al. 1999; El-Zaatari 2010). The abrasion marks tend to be  
551 thicker, shorter, with an isotropic distribution, more frequent on the most exposed parts of the

552 teeth (such as the cusps or the edges) and produce changes in the texture of the tooth enamel.  
553 The pits present an irregular morphology and also changes in relation to the enamel texture  
554 (**Fig. 3**).

555 Also, in previous experimental works, the presence of polished surfaces on the enamel surface  
556 of domestic caprines has been related to a higher intake of abrasive diets (e.g. Walker et al.  
557 1978; Mainland 1997; Jiménez-Manchón et al. 2020). This work shows that taphonomic  
558 enamel polishing appears on precise locations on the teeth according to the shape of the teeth  
559 (and so according to the species). Thus, the study of diet-related polished surfaces must be  
560 limited to the areas least sensitive to taphonomic alterations.

561 Loss of dietary features, scratches and pits could represent a limitation for microwear  
562 research. Dental microwear analyses are based on the quantitative analysis of these features. If  
563 they disappear due to taphonomic alterations, then it is no longer possible to correctly  
564 characterise an individual's diet. Ignoring the presence of alterations in an archaeological or  
565 paleontological assemblage could lead to misinterpretation and errors. For this reason,  
566 microwear studies should include a taphonomic analysis of the occlusal surface before  
567 observing and analysing the microwear features. The taphonomic study should include  
568 identification of the features described in the paper, with consideration of their location on the  
569 surface and their quantity. This would allow the location of areas suitable for microwear  
570 analysis. Areas with polished surfaces are not suitable for microwear as the original  
571 microwear patterns have been completely erased. The microwear analysis should be limited to  
572 teeth presenting as being well-preserved, non-altered surfaces of enamel. In this sense, our  
573 experimental work has shown that polishing did not affect all the occlusal surfaces in the  
574 same way. In general, equid enamel is more robust than that of suids and caprid. In equids, the  
575 evidence of abrasion first appears at the edges of the occlusal surface. For wild boar, the tips  
576 of the cusps are the more fragile part of the teeth and the first area where abrasion is  
577 documented. However, we have observed that other areas less exposed to abrasion (such as  
578 the base of the cusps of the wild boar tooth, or the enamel areas in the middle of the occlusal  
579 surface of the equid), remain unaltered over a much longer time of exposure to abrasion.  
580 Statistical analyses show that the increase in the number of features is generally low and does  
581 not have a significant impact on the interpretation of an individual's diet until the texture of  
582 the enamel is completely altered. Nevertheless, as a precaution, observers should reserve their  
583 studies for the best-preserved portions of teeth and discard those which present alterations on  
584 the whole occlusal surface. This does not occur in the case of goats, probably as a  
585 consequence of the specific morphology of selenodont teeth.

586

## 587 **5. Conclusions**

588

589 Our study aimed to evaluate the impact of a taphonomic alteration corresponding to sediment  
590 abrasion, tumbling, on the dental microwear patterns from occlusal enamel surfaces. Our  
591 analyses showed that these alterations had a different impact according to the sediment used  
592 and the taxa. Indeed, fine particles such as the mix of sand and clay sediment polish the  
593 enamel surfaces more, thus producing more alterations than the more abrasive but larger  
594 particles of sand. Polishing the enamel surface implies the progressive disappearance of part  
595 of the microwear features, thus leading to a quantitative error in the analysis, because the  
596 counting of scratches and pits would be biased by this alteration and would entail erroneous  
597 interpretations about the diet of the individuals studied. Therefore, we can conclude that in the  
598 areas where evidence of polishing of the enamel is documented, microwear studies cannot be  
599 carried out. However, it has been observed that polishing appears at different times during the  
600 experiment in the case of equid and wild boar teeth. In the case of wild boar, the tips of the  
601 cusps are the first where abrasion is documented, while at the base of the cusps there is no

602 evidence of alteration. In the case of the equid, the abrasion appears first at the edges of the  
603 occlusal surface, while the enamel in the centre of the surface remains unaltered. For this  
604 reason, we propose that the study of these preserved areas is valid even if there is evidence of  
605 abrasion in the most exposed areas. In any case, the abrasion marks that were produced during  
606 tumbling are different from the original dietary pits and scratches. It is possible, with some  
607 training by experienced researchers, to identify and discard them from the microwear  
608 quantification.

609  
610

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### 625 **References**

626  
627

627 Ackermans NL, Martin LF, Codron D, Hummel J, Kircher PR, Richter H., Kaiser TM, Clauss  
628 M, Hatt JM (2020) Mesowear represents a lifetime signal in sheep (*Ovis aries*) within a long-  
629 term feeding experiment. *Palaeogeography, Palaeoclimatology, Palaeoecology* 553, 109793.  
630 doi:10.1016/j.palaeo.2020.109793

631  
632

633 Baker G, Jones LHP, Wardrop ID (1959) Cause of Wear in Sheeps’ Teeth. *Nature* 184: 1583–  
634 1584. doi:10.1038/1841583b0

635  
636

636 Behrensmeyer AK (1978) Taphonomic and ecologic information from bone weathering.  
637 *Paleobiology* 4: 150–162.

638  
639

639 Behrensmeyer AK, Gordon KD, Yanagi GT (1986) Trampling as a cause of bone surface  
640 damage and pseudo-cutmarks. *Nature* 319: 768-771.

641  
642

642 Behrensmeyer AK, Gordon KD, Yanagi GT (1989) Nonhuman Bone Modification in  
643 Miocene Fossils from Pakistan. In: Bonnicksen R, Sorg MH (Eds.), *Bone Modification*.  
644 Orono: University of Maine Center for the Study of the First Americans, pp. 90-120.

645  
646

646 Böhm K, Winkler DE, Kaiser TM, Tütken T (2019) Post-mortem alteration of diet-related  
647 enamel surface textures through artificial biostratinomy: A tumbling experiment using  
648 mammal teeth. *Palaeogeography, Palaeoclimatology, Palaeoecology* 518: 215–231.  
649 doi:10.1016/j.palaeo.2019.01.008

650

651 Butler PM (1952) The milk-molars of Perissodactyla, with remarks on molar occlusion.  
652 Proceedings of the Zoological Society of London 121: 777–817. doi:10.1111/j.1096-  
653 3642.1952.tb00784.x  
654  
655 Calandra I, Merceron G (2016) Dental microwear texture analysis in mammalian ecology.  
656 Mammal Review 46: 215–228. doi:10.1111/mam.12063  
657  
658  
659 Currey JD (1999) The design of mineralised hard tissues for their mechanical functions.  
660 Journal of Experimental Biology 202: 3285–3294.  
661  
662 Dauphin Y, Castillo-Michel H, Denys C, El Hajraoui MA, Nespoulet R, Stoetzel E (2018)  
663 Diagenetic alterations of Meriones incisors (Rodentia) of El Harhoura 2 cave, Morocco (late  
664 Pleistocene–middle Holocene). Paläontologische Zeitschrift 92: 163–177.  
665 doi:10.1007/s12542-017-0382-4  
666  
667 Davis M, Pineda Munoz S (2016) The temporal scale of diet and dietary proxies. Ecology and  
668 Evolution 6: 1883–1897. doi:10.1002/ece3.2054  
669  
670 De Santis LRG, Scott JR, Schubert BW, Donohue SL, McCray BM, Van Stolk CA, Winburn  
671 AA, Greshko MA, O’Hara MC (2013) Direct Comparisons of 2D and 3D Dental Microwear  
672 Proxies in Extant Herbivorous and Carnivorous Mammals. PLoS ONE 8: e71428.  
673  
674 Domínguez-Rodrigo M, de Juana S, Galán AB, Rodríguez M (2009) A new protocol to  
675 differentiate trampling marks from butchery cut marks. Journal of Archaeological Science 36:  
676 2643–2654.  
677  
678 El-Zaatari S (2010) Occlusal microwear texture analysis and the diets of historical/prehistoric  
679 hunter-gatherers. International Journal of Osteoarchaeology 20: 67–87. doi:10.1002/oa.1027  
680  
681 Fernández-Jalvo Y, Andrews P (2003) Experimental Effects of Water Abrasion on Bone  
682 Fragments. Journal of Taphonomy 1: 147–163.  
683  
684  
685 Fortelius M (1985) Ungulate cheek teeth: developmental, functional, and evolutionary  
686 interrelations. Acta zoologica Fennica 180: 1–76.  
687  
688 Fox CL, Pérez-Pérez A, Juan J (1994) Dietary Information through the Examination of Plant  
689 Phytoliths on the Enamel Surface of Human Dentition. Journal of Archaeological Science 21:  
690 29–34. doi:10.1006/jasc.1994.1005  
691  
692 Fox CL, Juan J, Albert RM (1996) Phytolith analysis on dental calculus, enamel surface, and  
693 burial soil: Information about diet and paleoenvironment. American Journal of Physical  
694 Anthropology 101: 101–113. doi:10.1002/(SICI)1096-8644(199609)101:1<101::AID-  
695 AJPA7>3.0.CO;2-Y  
696  
697 Galbany J, Estebaranz F, Martínez LM, Romero A, De Juan J, Turbón D, Pérez-Pérez A  
698 (2006) Comparative analysis of dental enamel polyvinylsiloxane impression and polyurethane  
699 casting methods for SEM research. Microscopy Research and Technique 69: 246–252.  
700 doi:10.1002/jemt.20296

701  
702 Gallego A, Rivals F, Colominas L, Palet JM (2017) Pastando en las marismas. Una  
703 aproximación desde la técnica del desgaste dentario a la alimentación del ganado ovino en el  
704 Empordà romano (noreste de la Península Ibérica). *Pyrenae* 48: 93-113.  
705  
706 Gaudzinski-Windheuser S, Kindler L, Rabinovich R, Goren-Inbar N (2010) Testing  
707 heterogeneity in faunal assemblages from archaeological sites. Tumbling and trampling  
708 experiments at the early-Middle Pleistocene site of Gesher Benot Ya'akov (Israel). *Journal of*  
709 *Archaeological Science* 37: 3170-3190.  
710  
711 Gordon KD (1983) Taphonomy of dental microwear: can fossil microwear be studied  
712 productively? *American Journal of Physical Anthropology* 60: 200.  
713  
714 Gordon KD (1984) Taphonomy of dental microwear. *American Journal of Physical*  
715 *Anthropology* 64: 164–165.  
716  
717 Grine FE (1977) Analysis of early hominid deciduous molar wear by scanning electron  
718 microscopy: a preliminary report. *Proceedings of the Electron Microscopy, Society of South*  
719 *Africa* 7: 157–158.  
720  
721 Grine FE, Krause DW, Fosse G, Jungers WL (1987) Analysis of individual, intraspecific and  
722 interspecific variability in quantitative parameters of caprine tooth enamel structure. *Acta*  
723 *Odontologica Scandinavica* 45: 1–23. doi:10.3109/00016358709094349  
724  
725  
726 Janis C (1976) The Evolutionary Strategy of the Equidae and the Origins of Rumen and Cecal  
727 Digestion. *Evolution* 30: 757–774. doi:10.2307/2407816  
728  
729 Janis C (1988) An estimation of tooth volume and hypsodonty indices in ungulate mammals,  
730 and the correlation of these factors with dietary preference. In: Russell DE, Santoro JP,  
731 Sigogneau-Russell D (eds.), *Teeth Revisited*. Presented at the Proceedings of the VIIth  
732 international symposium on dental morphology, Mémoires du Muséum National d'Histoire  
733 Naturelle, Paris, pp. 367–387.  
734  
735 Janis, CM (1995) Correlation between craniodental morphology and feeding behavior in  
736 ungulates: reciprocal illumination between living and fossil taxa. In: Thomason JJ (ed.),  
737 *Functional Morphology in Vertebrate Paleontology*. Cambridge University Press, Cambridge,  
738 pp. 76–98.  
739  
740 Jiménez-Manchón S, Valenzuela-Lamas S, Cáceres I, Orengo H, Gardeisen A, López D,  
741 Rivals F (2019) Reconstruction of caprine management and landscape use through dental  
742 microwear analysis: the case of the Iron age site of el Turó de la Font de la Canya (Barcelona,  
743 Spain). *Environmental Archaeology* 24: 303-316.  
744  
745 Jiménez-Manchón S, Blaise É, Gardeisen A (2020) Exploring low-magnification dental  
746 microwear of domestic ungulates: Qualitative observations to infer palaeodiets. *Quaternary*  
747 *International*. doi:10.1016/j.quaint.2020.02.021  
748



749 King T, Andrews P, Boz B (1999) Effect of taphonomic processes on dental microwear.  
750 American Journal of Physical Anthropology 108: 359–373. doi:10.1002/(SICI)1096-  
751 8644(199903)108:3<359::AID-AJPA10>3.0.CO;2-9  
752  
753 Kozawa Y, Mishima H, Sakae T (1988) Evolution of tooth structure in the Equoidea. The  
754 Journal of Nihon University School of Dentistry 30: 287–296.  
755 doi:10.2334/josnusd1959.30.287  
756  
757 Krueger KL, Scott JR, Kay RF, Ungar PS (2008) Technical note: Dental microwear textures  
758 of “Phase I” and “Phase II” facets. American Journal of Physical Anthropology 137: 485–490.  
759 doi:10.1002/ajpa.20928  
760  
761 Lyman RL (1994) Vertebrate Taphonomy. Cambridge, University Press.  
762  
763 Mainland IL (1997) A qualitative approach to dental microwear analysis. In: Sinclair ARE,  
764 Slater E, Gowlett J (eds.), Archaeological Sciences 1995: Proceedings of a Conference on the  
765 Application of Scientific Methods to Archaeology. Oxbow Books Monograph Series, Oxford,  
766 pp. 213–221.  
767  
768 Mainland IL (2003) Dental Microwear in Grazing and Browsing Gotland Sheep (*Ovis aries*)  
769 and its Implications for Dietary Reconstruction. Journal of Archaeological Science 30: 1513-  
770 1527.  
771  
772 Mainland IL (2006) Pastures Lost? A Dental Microwear Study of Ovicaprine Diet and  
773 Management in Norse Greenland. Journal of Archaeological Science 33: 238-252.  
774  
775 Martínez LM, Pérez-Pérez A (2004) Post-mortem wear as indicator of taphonomic processes  
776 affecting enamel surfaces of hominin teeth from Laetoli and Olduvai (Tanzania): implications  
777 to dietary interpretations. Anthropology XLII/I: 37–42.  
778  
779 Mendoza M, Janis CM, Palmqvist P (2002) Characterizing complex craniodental patterns  
780 related to feeding behaviour in ungulates: a multivariate approach. Journal of Zoology 258:  
781 223–246. doi:10.1017/S0952836902001346  
782  
783 Mihlbachler MC, Beatty BL, Caldera-Siu A, Chan D, Lee R (2012) Error rates and observer  
784 bias in dental microwear analysis using light microscopy. Palaeontologia Electronica 15: 22 p.  
785  
786 Mihlbachler MC, Foy M, Beatty BL (2019) Surface replication, fidelity and data loss in  
787 traditional dental microwear and dental microwear texture analysis. Scientific Report 9: 1595.  
788  
789 Mills JRE (1955) Ideal dental occlusion in the primates. Dental Practitioner 6: 47–61.  
790  
791 Muylle S, Simoens P, Verbeeck R, Ysebaert MT, Lauwers H (1999) Dental wear in horses in  
792 relation to the microhardness of enamel and dentine. The Veterinary Record 144: 558–561.  
793 doi:10.1136/vr.144.20.558  
794  
795  
796  
797

798 Pineda A, Cáceres I, Saladié P, Huguet R, Morales JI, Rosas A, Vallverdú J (2019) Tumbling  
799 effects on bone surface modifications (BSM): An experimental application on archaeological  
800 deposits from the Barranc de la Boella site (Tarragona, Spain). *Journal of Archaeological*  
801 *Science* 102: 35-47.  
802  
803 Popowics TE, Rensberger JM, Herring SW (2004) Enamel microstructure and microstrain in  
804 the fracture of human and pig molar cusps. *Archives of Oral Biology* 49: 595–605.  
805 doi:10.1016/j.archoralbio.2004.01.016  
806  
807 Popowics TE, Herring SW (2006) Teeth, jaws and muscles in mammalian mastication. In:  
808 Bels, V. (Ed.), *Feeding in Domestic Vertebrates: From Structure to Behaviour*. Cabi, pp. 61–  
809 83.  
810  
811 Puech PF, Prone A, Roth H, Cianfarani F (1985) Reproduction expérimentale de processus  
812 d'usure des surfaces dentaires des Hominidés fossiles : conséquences morphoscopiques et  
813 exoscopiques avec application à l'Hominidé I de Garusi. *Compte rendu de l'Académie des*  
814 *sciences de Paris* 301, 59–64.  
815  
816 Rabinovich R, Gaudzinski-Windheuser S, Kindler L, Goren-Inbar N (2012) The Acheulian  
817 Site of Gesher Benot Ya'aqov -Volume III - Mammalian Taphonomy. *The Assemblages of*  
818 *Layers V-5 and V-6*. Netherlands: Springer.  
819  
820 Rigdon EE (1999) Using the Friedman method of ranks for model comparison in structural  
821 equation modeling. *Structural Equation Modeling: A Multidisciplinary Journal* 6: 219–232.  
822 doi:10.1080/10705519909540131  
823  
824 Rivals F (2012) Ungulate feeding ecology and middle Pleistocene paleoenvironments at  
825 Hundsheim and Deutsch-Altenburg 1 (eastern Austria). *Palaeogeography, Palaeoclimatology,*  
826 *Palaeoecology* 317–318: 27–31. doi:10.1016/j.palaeo.2011.12.006  
827  
828 Rivals F, Uzunidis A, Sanz M, Daura J (2017) Faunal dietary response to the Heinrich Event  
829 4 in southwestern Europe. *Palaeogeography, Palaeoclimatology, Palaeoecology* 473: 123–  
830 130. doi:10.1016/j.palaeo.2017.02.033  
831  
832 Rivals F, Kitagawa K, Julien MA, Patou-Mathis M, Bessudnov AA, Bessudnov AN (2018)  
833 Straight from the horse's mouth: High-resolution proxies for the study of horse diet and its  
834 relation to the seasonal occupation patterns at Divnogor'ye 9 (Middle Don, Central Russia).  
835 *Quaternary International* 474: 146–155. doi:10.1016/j.quaint.2018.01.008  
836  
837 Rozada L, Allain R, Tournepiche JF (2018) Trampling experiments on bones in fine and soft  
838 sediments. *Quaternaire*:39–44. doi:10.4000/quaternaire.8593  
839  
840 Sánchez-Hernández C, Rivals F, Blasco R, Rosell J (2016) Tale of two timescales:  
841 Combining tooth wear methods with different temporal resolutions to detect seasonality of  
842 Palaeolithic hominin occupational patterns. *Journal of Archaeological Science: Reports* 6:  
843 790–797. doi:10.1016/j.jasrep.2015.09.011  
844  
845 Scott RS, Ungar PS, Bergstrom TS, Brown CA, Childs BE, Teaford MF, Walker A (2006)  
846 Dental microwear texture analysis: technical considerations. *Journal of Human Evolution* 51:  
847 339–349. doi:10.1016/j.jhevol.2006.04.006

848  
849 Scott RS, Ungar PS, Bergstrom TS, Brown CA, Grine FE, Teaford MF, Walker A (2005)  
850 Dental microwear texture analysis shows within-species diet variability in fossil hominins.  
851 Nature 436: 693–695.  
852  
853 Semprebon G, Godfrey LR, Solounias N, Sutherland MR, Jungers WL (2004a) Can low-  
854 magnification stereomicroscopy reveal diet? Journal of Human Evolution: 115–144.  
855  
856 Semprebon G, Janis C, Solounias N (2004b) The diets of the Dromomerycidae (Mammalia:  
857 Artiodactyla) and their response to Miocene vegetational change. Journal of Vertebrate  
858 Paleontology 24: 427–444. doi:10.1671/2431  
859  
860 Semprebon GM, Rivals F (2007) Was grass more prevalent in the pronghorn past? An  
861 assessment of the dietary adaptations of Miocene to Recent Antilocapridae (Mammalia:  
862 Artiodactyla). Palaeogeography, Palaeoclimatology, Palaeoecology 253: 332–347.  
863 doi:10.1016/j.palaeo.2007.06.006  
864  
865 Solounias N, Teaford M, Walker A (1988) Interpreting the diet of extinct ruminants: the case  
866 of a non-browsing giraffid. Paleobiology 14: 287–300. doi:10.1017/S009483730001201X  
867  
868 Solounias N, Moelleken SMC (1993a) Dietary Adaptation of Some Extinct Ruminants  
869 Determined by Premaxillary Shape. Journal of Mammalogy 74: 1059–1971.  
870 doi:10.2307/1382445  
871  
872 Solounias N, Moelleken SMC (1993b) Tooth microwear and premaxillary shape of an archaic  
873 antelope. Lethaia 26: 261–268. doi:10.1111/j.1502-3931.1993.tb01529.x  
874  
875 Solounias N, Hayek LAC (1993) New methods of tooth microwear analysis and application to  
876 dietary determination of two extinct antelopes. Journal of Zoology 229: 421–445.  
877 doi:10.1111/j.1469-7998.1993.tb02646.x  
878  
879 Solounias N, Semprebon G (2002) Advances in the reconstruction of ungulate  
880 ecomorphology with application to early fossil equids. American museum novitates 3366: 49.  
881  
882 Shipman P, Rose J (1983) Early Hominid Hunting, Butchering, and Carcass-Processing  
883 Behaviors: Approaches to the Fossil Record. Journal of Anthropological Archaeology 2: 57-  
884 98.  
885  
886 Teaford MF (1988) Scanning electron microscope diagnosis of wear patterns versus artifacts  
887 on fossil teeth. Scanning Microscopy 2: 1167–1175.  
888  
889 Ungar PS, Scott RS, Grine FE, Teaford MF (2010) Molar microwear textures and the diets of  
890 *Australopithecus anamensis* and *Australopithecus afarensis*. Philosophical Transactions of the  
891 Royal Society B: Biological Sciences 365: 3345–3354. doi:10.1098/rstb.2010.0033  
892  
893 Uzunidis A (2020) Dental wear analyses of Middle Pleistocene site of Lunel-Viel (Hérault,  
894 France): Did *Equus* and *Bos* live in a wetland? Quaternary International.  
895 doi:10.1016/j.quaint.2020.04.011  
896

897 Vázquez-Correa MC, Rodas HL (2019) A robust approach for principal component analysis.  
 898 arXiv:1903.00093 [math, stat].  
 899  
 900 Walker A, Hoeck HN, Perez L (1978) Microwear of mammalian teeth as an indicator of diet.  
 901 Science (New York, N.Y.) 201: 908–910.  
 902  
 903 Waters NE (1980) Some mechanical and physical properties of teeth. In: Vincent, JFV,  
 904 Currey JD (eds.), The Mechanical Properties of Biological Materials. London, pp. 99–135.  
 905  
 906 Weber K, Winkler DE, Kaiser TM, Žigaitė Ž, Tütken T (2020) Dental microwear texture  
 907 analysis on extant and extinct sharks: Ante- or post-mortem tooth wear? Palaeogeography,  
 908 Palaeoclimatology, Palaeoecology: 110147. doi:10.1016/j.palaeo.2020.110147  
 909  
 910 Williams VS, Doyle AM (2010) Cleaning fossil tooth surfaces for microwear analysis: Use of  
 911 solvent gels to remove resistant consolidant. Palaeontologia Electronica 13: 12 p.  
 912  
 913 Xafis A, Nagel D, Bastl K (2017) Which tooth to sample? A methodological study of the  
 914 utility of premolar/non-carnassial teeth in the microwear analysis of mammals.  
 915 Palaeogeography Palaeoclimatology Palaeoecology 487: 229–240.  
 916 doi:10.1016/j.palaeo.2017.09.003  
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918 **Table captions**

Group	Number of teeth				Type of sediment	Time of exposition
	<i>Equus</i> sp.	<i>Capra hircus</i>	<i>Sus scrofa</i>	Total		
G1	2	10		<b>12</b>	Mix of sand and clay	2h (6 cycles)
G2			15	<b>15</b>		
G3	3	9		<b>12</b>	Sand	
G4			14	<b>14</b>		

919  
 920 Table 1: Groups used in the tumbling experiment: taxa, number of teeth, sediment type and  
 921 time of exposition.  
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Sediment	Cycle	Time in the tumbler	Total time	N	Large pits	Small pits	Fine scratches	Coarse scratches	Hyper-coarse scratches	Cross scratches	Gouges
Sand-clay	0	0 min	0 min	5 m	<b>1.60</b>	<b>17.60</b>	<b>4.20</b>	<b>0.40</b>	<b>0.00</b>	<b>0.20</b>	<b>0.00</b>
				s	1.34	6.19	0.84	0.89	0.00	0.45	0.00
Sand-clay	1	2 min	2 min	5 m	<b>1.80</b>	<b>18.00</b>	<b>5.00</b>	<b>0.40</b>	<b>0.00</b>	<b>0.20</b>	<b>0.00</b>
				s	1.30	4.36	2.83	0.89	0.00	0.45	0.00
Sand-clay	2	3 min	5 min	5 m	<b>2.40</b>	<b>20.40</b>	<b>6.00</b>	<b>1.00</b>	<b>0.00</b>	<b>0.80</b>	<b>0.00</b>
				s	1.67	3.71	2.00	1.73	0.00	1.10	0.00
Sand-clay	3	10 min	15 min	5 m	<b>1.80</b>	<b>23.00</b>	<b>7.60</b>	<b>0.40</b>	<b>0.00</b>	<b>1.00</b>	<b>0.00</b>
				s	1.30	7.11	2.41	0.55	0.00	1.41	0.00
Sand-clay	4	15 min	30 min	5 m	<b>3.00</b>	<b>28.40</b>	<b>6.80</b>	<b>0.20</b>	<b>0.20</b>	<b>0.00</b>	<b>0.00</b>
				s	2.12	15.53	3.11	0.45	0.45	0.00	0.00
Sand	0	0 min	0 min	5 m	<b>0.80</b>	<b>25.40</b>	<b>10.20</b>	<b>0.00</b>	<b>0.00</b>	<b>1.00</b>	<b>0.00</b>
				s	1.79	8.93	4.66	0.00	0.00	0.71	0.00
Sand	1	2 min	2 min	5 m	<b>0.60</b>	<b>24.60</b>	<b>9.60</b>	<b>0.00</b>	<b>0.00</b>	<b>1.00</b>	<b>0.00</b>
				s	0.89	9.45	3.05	0.00	0.00	0.71	0.00
Sand	2	3 min	5 min	5 m	<b>1.40</b>	<b>24.60</b>	<b>9.80</b>	<b>0.00</b>	<b>0.00</b>	<b>1.00</b>	<b>0.00</b>
				s	1.34	9.69	3.11	0.00	0.00	0.71	0.00
Sand	3	10 min	15 min	5 m	<b>1.40</b>	<b>20.60</b>	<b>9.00</b>	<b>0.00</b>	<b>0.00</b>	<b>1.00</b>	<b>0.00</b>
				s	1.34	4.04	3.08	0.00	0.00	0.71	0.00
Sand	4	15 min	30 min	5 m	<b>0.20</b>	<b>23.20</b>	<b>10.60</b>	<b>0.00</b>	<b>0.00</b>	<b>1.20</b>	<b>0.00</b>
				s	0.45	6.83	2.07	0.00	0.00	0.84	0.00
Sand	5	30 min	60 min	5 m	<b>0.40</b>	<b>19.80</b>	<b>8.20</b>	<b>0.00</b>	<b>0.00</b>	<b>1.80</b>	<b>0.00</b>
				s	0.89	5.07	2.49	0.00	0.00	0.45	0.00
Sand	6	60 min	120 min	5 m	<b>0.00</b>	<b>22.20</b>	<b>7.00</b>	<b>0.00</b>	<b>0.00</b>	<b>1.40</b>	<b>0.40</b>
				s	0.00	8.41	2.12	0.00	0.00	0.55	0.89
Sediment	Cycle	Time in the tumbler	Total time	N	Large pits	Small pits	Fine scratches	Coarse scratches	Hyper-coarse scratches	Cross scratches	Gouges

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929 Table 2: Summary of the data for the teeth of *Capra hircus* in sand and in the mix of sand and  
930 clay sediment. N = number of teeth; m = mean; s = standard deviation.

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Sand-clay	0	0 min	0 min	1	n°I.7	7	24	9	4	0	1	0
Sand-clay	1	2 min	2 min	1	n°I.7	6	24	10	4	0	2	0
Sand-clay	2	3 min	5 min	1	n°I.7	4	22	12	2	0	2	0
Sand-clay	3	10 min	15 min	1	n°I.7	4	23	12	3	0	2	0
Sand-clay	4	15 min	30 min	1	n°I.7	3	23	14	2	0	0	3
Sand-clay	5	30 min	60 min	1	n°I.7	4	26	10	4	0	4	0
Sand	0	0 min	0 min	3	m s	<b>0.00</b> 0.00	<b>11.33</b> 5.51	<b>18.00</b> 6.08	<b>0.00</b> 0.00	<b>0.00</b> 0.00	<b>0.00</b> 0.00	<b>0.00</b> 0.00
Sand	1	2 min	2 min	3	m s	<b>0.00</b> 0.00	<b>12.67</b> 3.06	<b>17.33</b> 6.66	<b>0.00</b> 0.00	<b>0.00</b> 0.00	<b>0.67</b> 0.58	<b>0.00</b> 0.00
Sand	2	3 min	5 min	3	m s	<b>0.00</b> 0.00	<b>15.00</b> 3.61	<b>17.00</b> 4.36	<b>0.00</b> 0.00	<b>0.00</b> 0.00	<b>0.67</b> 0.58	<b>0.00</b> 0.00
Sand	3	10 min	15 min	3	m s	<b>0.00</b> 0.00	<b>12.33</b> 0.58	<b>16.33</b> 5.86	<b>0.00</b> 0.00	<b>0.00</b> 0.00	<b>2.00</b> 1.00	<b>0.00</b> 0.00
Sand	4	15 min	30 min	3	m s	<b>0.67</b> 1.15	<b>10.67</b> 2.52	<b>16.33</b> 2.31	<b>0.00</b> 0.00	<b>0.00</b> 0.00	<b>1.00</b> 1.00	<b>0.00</b> 0.00
Sand	5	30 min	60 min	3	m s	<b>3.00</b> 3.00	<b>12.00</b> 2.65	<b>15.33</b> 3.06	<b>0.67</b> 0.58	<b>0.00</b> 0.00	<b>1.67</b> 0.58	<b>0.00</b> 0.00
Sand	6	60 min	120 min	3	m s	<b>4.00</b> 3.61	<b>15.33</b> 1.15	<b>13.33</b> 6.51	<b>0.33</b> 0.58	<b>0.00</b> 0.00	<b>1.33</b> 0.58	<b>0.33</b> 0.58
Sediment	Cycle	Time in the tumbler	Total time	N		Large pits	Small pits	Fine scratches	Coarse scratches	Hyper- coarse scratches	Cross scratches	Gouges

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937 Table 3: Summary of the data for the teeth of *Equus* sp. in sand and in the mix of sand and

938 clay sediment. N = number of teeth; m = mean; s = standard deviation.

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Sand-Clay	0	0 min	0 min	6 m	<b>3.50</b>	<b>7.33</b>	<b>9.00</b>	<b>4.83</b>	<b>1.17</b>	<b>1.00</b>	<b>0.33</b>
				s	3.08	2.16	2.53	1.72	1.17	0.00	0.82
Sand-Clay	1	2 min	2 min	6 m	<b>3.33</b>	<b>8.17</b>	<b>8.83</b>	<b>4.83</b>	<b>1.17</b>	<b>1.00</b>	<b>0.33</b>
				s	2.80	2.48	2.48	1.72	1.17	0.00	0.82
Sand-Clay	2	3 min	5 min	6 m	<b>4.00</b>	<b>9.17</b>	<b>9.17</b>	<b>5.33</b>	<b>1.50</b>	<b>1.00</b>	<b>0.67</b>
				s	3.41	2.23	3.31	2.16	1.64	0.00	1.03
Sand-Clay	3	10 min	15 min	6 m	<b>5.83</b>	<b>9.17</b>	<b>9.33</b>	<b>6.67</b>	<b>2.33</b>	<b>1.00</b>	<b>3.50</b>
				s	5.49	3.43	6.35	2.42	2.25	0.00	3.89
Sand	0	0 min	0 min	8 m	<b>6.50</b>	<b>20.75</b>	<b>22.38</b>	<b>4.38</b>	<b>1.00</b>	<b>6.63</b>	<b>0.38</b>
				s	1.85	3.49	3.38	0.92	0.76	1.06	0.52
Sand	1	2 min	2 min	8 m	<b>6.63</b>	<b>18.75</b>	<b>23.13</b>	<b>5.25</b>	<b>1.00</b>	<b>8.13</b>	<b>0.13</b>
				s	2.07	1.98	2.59	1.04	0.53	1.64	0.35
Sand	2	3 min	5 min	8 m	<b>8.88</b>	<b>16.38</b>	<b>23.25</b>	<b>6.25</b>	<b>0.88</b>	<b>7.00</b>	<b>0.38</b>
				s	2.10	2.20	1.67	1.67	0.64	0.93	0.52
Sand	3	10 min	15 min	8 m	<b>7.13</b>	<b>15.13</b>	<b>21.38</b>	<b>6.88</b>	<b>0.75</b>	<b>6.63</b>	<b>0.25</b>
				s	1.64	2.36	2.07	1.46	0.71	1.51	0.46
Sand	4	15 min	30 min	8 m	<b>6.25</b>	<b>16.38</b>	<b>20.25</b>	<b>6.38</b>	<b>0.88</b>	<b>6.38</b>	<b>0.63</b>
				s	1.49	2.45	2.96	1.30	0.64	2.92	0.52
Sand	5	30 min	60 min	8 m	<b>6.88</b>	<b>15.88</b>	<b>21.38</b>	<b>6.38</b>	<b>1.25</b>	<b>7.00</b>	<b>0.38</b>
				s	2.23	2.95	2.07	1.85	0.46	2.33	0.52
Sand	6	60 min	120 min	8 m	<b>6.75</b>	<b>19.25</b>	<b>22.00</b>	<b>7.13</b>	<b>1.25</b>	<b>7.25</b>	<b>0.13</b>
				s	1.58	2.60	2.98	1.25	0.46	1.83	0.35

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Table 4: Summary of the data for the teeth of *Sus scrofa* in sand and in the mix of sand and clay sediment. N = number of teeth; m = mean; s = standard deviation.

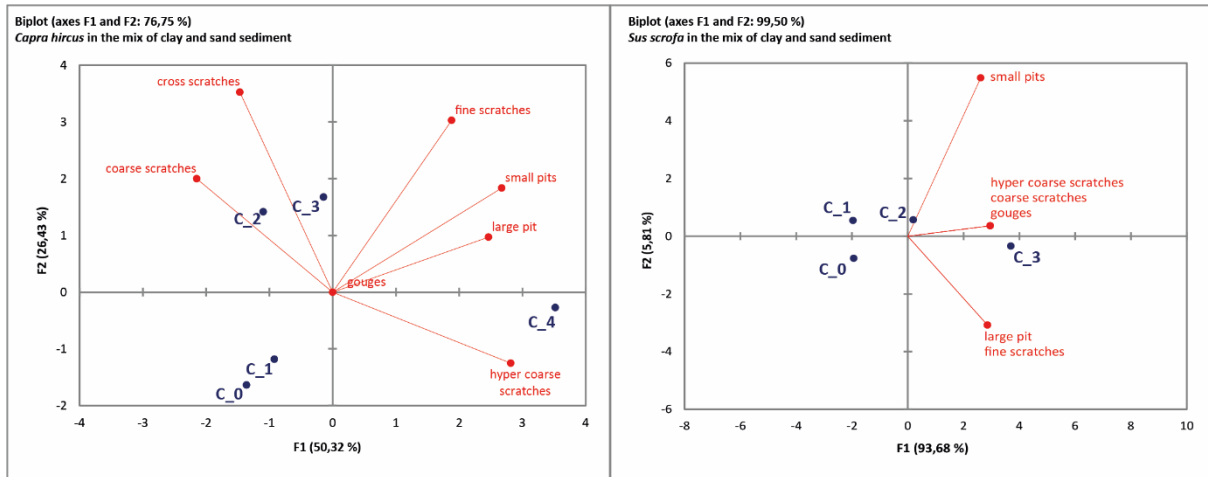
	Cycle	Duration of tumbing	<i>Equus sp.</i>		<i>Sus scrofa</i>		<i>Capra hircus</i>	
			N	%	N	%	N	%
Sand-Clay sediment	0	0 min	2	100	9	100	8	100
	1	2 min	2	100	9	100	8	100
	2	3 min	2	100	9	100	7	87.5
	3	10 min	2	100	6	66.7	6	75
	4	15 min	2	100	3	33.3	6	75
	5	30 min	1	50	2	22.2	2	25
	6	60 min	0	0	0	0	0	0
Sand sediment	0	0 min	3	100	13	100	9	100
	1	2 min	3	100	11	84.6	9	100
	2	3 min	3	100	9	69.2	7	77.8
	3	10 min	3	100	9	69.2	7	77.8
	4	15 min	3	100	9	69.2	7	77.8
	5	30 min	3	100	9	69.2	5	55.5
	6	60 min	3	100	8	61.5	5	55.5

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948 Table 5: Number of teeth analysed for microwear after each cycle of tumbling in the mix of  
 949 sand and clay sediment and sand sediments and percentage of teeth still suitable for  
 950 observation for each cycle compared to cycle 0.

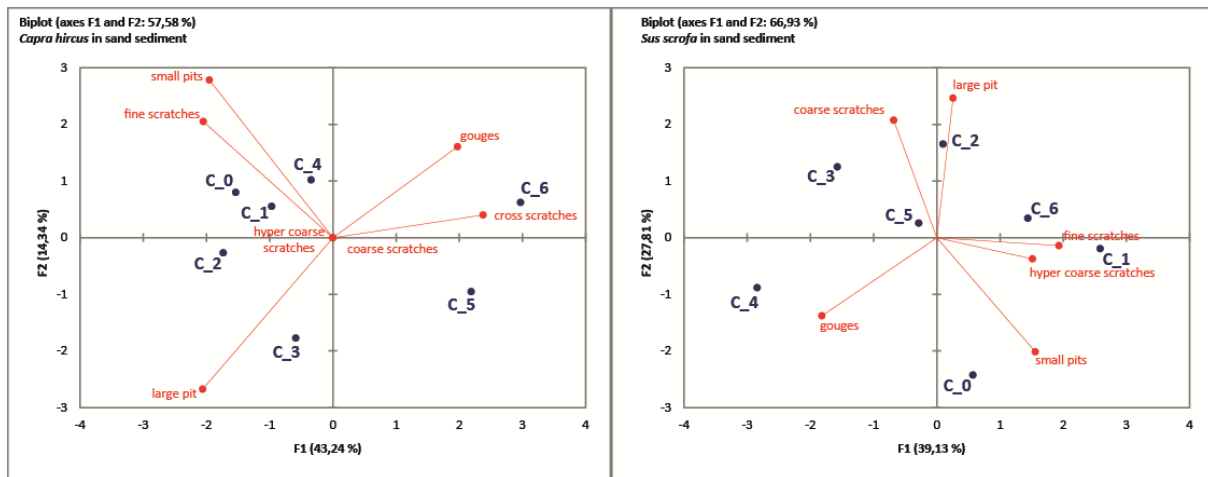
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**Figure captions**



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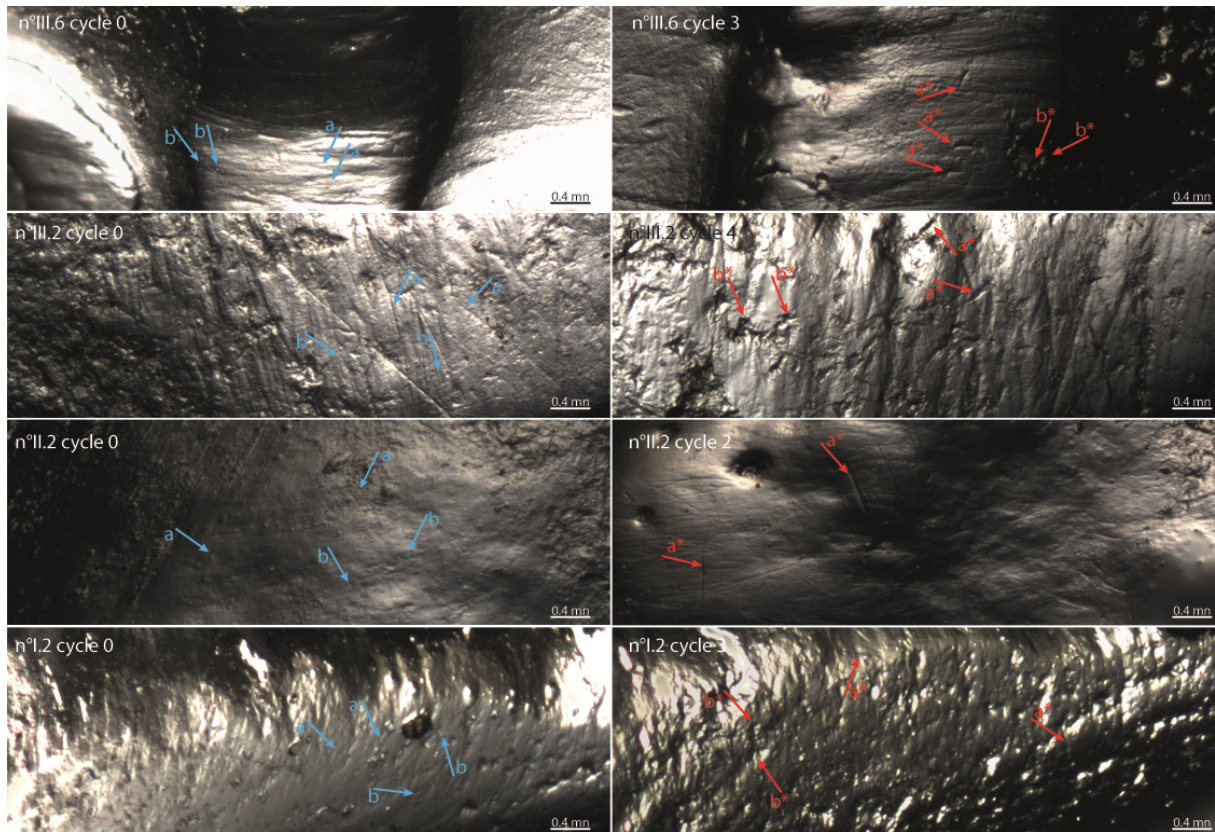
Figure 1: Principal Component Analysis (PCA) based on the microwear variables traditionally employed to characterise the dietary traits of herbivores on the tumbled teeth of *Sus scrofa* and *Capra hircus* in the mix of sand and clay sediment. The variables used are the number of fine, coarse, and hyper coarse scratches, the number of small and large pits, the number of gouges and cross scratches (except for *Sus scrofa*). Duration of the cycles of tumbling: C0 = 0 min; C1 = 2 min; C2 = 3 min; C3 = 10 min; C4 = 15 min.



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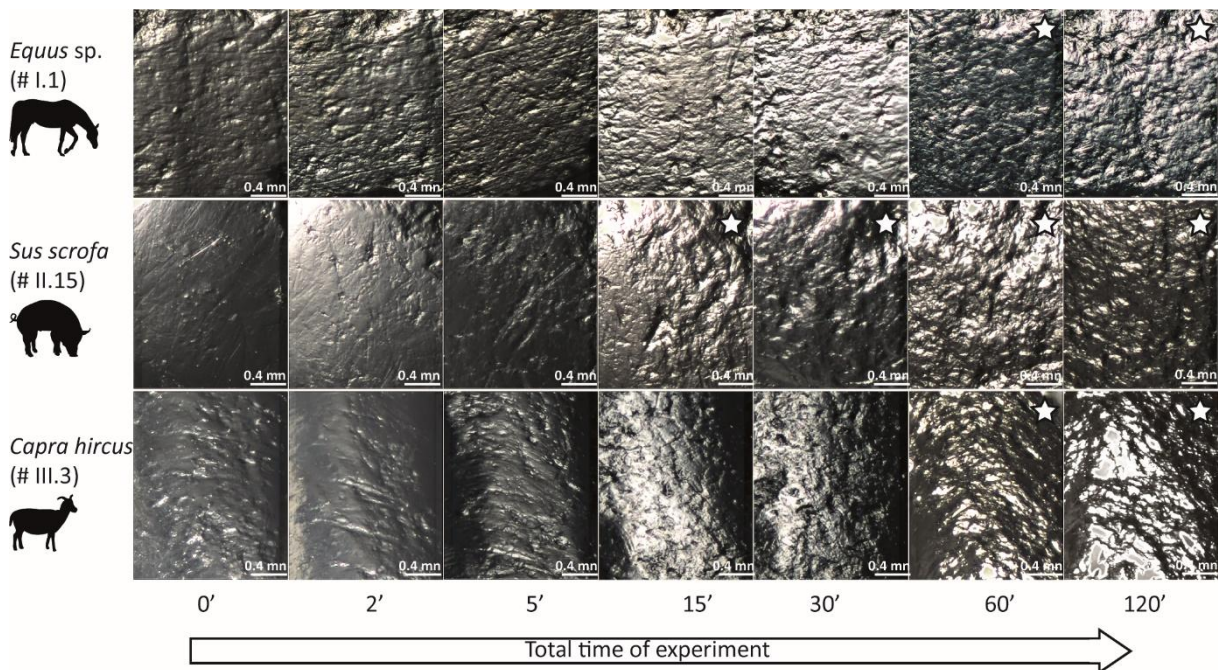
Figure 2: Principal Component Analysis (PCA) based on the microwear variables traditionally employed to characterise the dietary traits of herbivores on the tumbled teeth of *Sus scrofa* and *Capra hircus* in sand. The variables used are the number of fine, coarse, and hyper coarse scratches, the number of small and large pits, the number of gouges and cross scratches (except for *Sus scrofa*). Duration of the cycles of tumbling. C0 = 0 min; C1 = 2 min; C2 = 3 min; C3 = 10 min; C4 = 15 min; C5 = 30 min; C6 = 60 min.





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Figure 3: Examples of the morphology of taphonomic features compared to dietary features: a: dietary scratches; b: dietary pits; a\*: trampling marks; b\*: taphonomic pits. N°III.6 = *Equus* sp.; n°III.2 = *Equus* sp.; n°II.2 = *Sus scrofa*; n°I.2 = *Capra hircus*.



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Figure 4: Example of the evolution of the alterations over time (from the beginning to two hours of tumbling). The white stars indicate the moment when the dietary observations

986 become impossible. N°I.1 = *Equus* sp.; n°II.15 = *Sus scrofa*; n°III.3 = *Capra hircus*. Animal  
987 silhouettes downloaded from all-free-download.com.  
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