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3 **Calcium isotopic variability of cervid bioapatite and implications for mammalian**  
4 **physiology and diet**

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17 **Abstract**

18 There is clues that calcium (Ca) isotope composition of vertebrate bioapatite is  
19 influenced by diet and trophic level. These clues however conflict with several cases of  
20 mammal species exhibiting Ca isotope compositions which are inconsistent with their trophic  
21 levels. These observations support that diet may not be the only factor driving the Ca isotope  
22 composition in mammalian enamel and bone. To investigate this question, we selected a

23 modern *Cervus elaphus* population (Bauges Natural Regional Park, Alps, France) to serve as  
24 a model for Ca isotope physiology of cervids and other mammals. Subsequently, we  
25 reinvestigated the case of the fossil *Rangifer tarandus* population from Jaurens (Late  
26 Pleistocene locality, 32.6 to 29.7 kyr BP, France), a population for which abnormal  $^{44}\text{Ca}$ -  
27 depleted isotope compositions have been previously documented. By combining bone  
28 samplings and serial enamel micro-samplings, we discuss the main potential sources of Ca  
29 isotopic variability in bioapatite of young and adult individuals. This includes the effects of  
30 gestation, lactation, antlerogenesis, browser-grazer ecologies, osteophagia and natural mineral  
31 licks. Our results highlight an important effect of lactation on bone Ca isotope composition  
32 ( $\delta^{44/42}\text{Ca} = +0.18 \pm 0.07 \text{ ‰}$ ; 95 % confidence interval), whereas other factors such as gestation  
33 or antlerogenesis seem more secondary. Our enamel micro sampling method allowed to detect  
34 when enamel Ca isotope composition could be affected by milk consumption or mineral  
35 supplementation. Thanks to these advances, we collected new data from the Pleistocene  
36 reindeers of Jaurens which are now consistent with their apparent low trophic level  
37 (corresponding to a herbivorous diet). This demonstrates that disentangling ecological and  
38 physiological signals within enamel Ca isotope compositions is possible by using serial  
39 micro-sampling. This approach allows retrieving accurate trophic information from this proxy  
40 and which, altogether, truly push forward the limits of Ca isotope applications regarding  
41 paleoecology, physiology and ethology.

#### 42 **Keywords**

43 Stable isotopes; Geochemistry; Paleoecology; Lactation, Mineral supplementation; Mammal  
44 physiology

45 **1. Introduction**

46 An increasing number of studies suggest that the stable Ca isotope composition of the  
47 hydroxylapatite of vertebrate bone and teeth, represents a record of diet within modern and  
48 fossil skeletal remains (Clementz et al., 2003; Chu et al., 2006; Reynard et al., 2010; Heuser  
49 et al., 2011; Clementz, 2012; Martin et al., 2015, 2017a, 2017b, 2018; Hassler et al., 2018).  
50 Body Ca originates mainly from food and water for land animals, but the Ca isotope  
51 composition of animals diverges from their food. At the opposite of carbon and nitrogen  
52 patterns, heavy Ca isotopes are discriminated against light Ca isotopes during their routing  
53 from food to tissues, notably in bone and enamel (Skulan and DePaolo, 1999; Chu et al.,  
54 2006; Hirata et al., 2008; Tacail et al., 2014; Heuser, 2016; Heuser et al., 2016). This results  
55 in a trophic level effect (hereafter TLE) with bones of herbivorous animals exhibiting more  
56  $^{44}\text{Ca}$ -depleted compositions compared to the plants they consume, and carnivorous predators  
57 following the same trend compared to their preys. This ultimately leads to an isotopic  
58 clustering of animal taxa in function of their trophic level, with primary consumers exhibiting  
59 a heavier Ca isotope composition than tertiary consumers, and secondary consumers  
60 exhibiting an intermediate isotopic composition. This has been observed in land ecosystems  
61 (Chu et al., 2006; Reynard et al., 2010; Martin et al., 2017a, 2018; Hassler et al., 2018; Dodat  
62 et al., 2021) and marine ecosystems (Clementz et al., 2003; Clementz, 2012; Martin et al.,  
63 2015, 2017b), even though for marine animals the Ca originating from seawater likely buffers  
64 dietary Ca intakes. These studies are based on  $^{44}\text{Ca}/^{42}\text{Ca}$  or  $^{44}\text{Ca}/^{40}\text{Ca}$  analyses of the  
65 hydroxylapatite of bone and teeth, commonly expressed as  $\delta^{44/40}\text{Ca}$  and  $\delta^{44/40}\text{Ca}$ , respectively  
66 (equivalent to the variation in ‰ compared to the Ca isotope ratios of a reference material,  
67 further detailed in section 2.6). Moreover, this technic allows to study the ecology of both  
68 modern and fossil specimens thanks to the good preservation potential of such mineralized

69 tissues and their Ca (Heuser et al., 2011; Martin et al., 2017a). This body of studies supports  
70 that Ca isotopes are a promising tool for diet and trophic inferences in modern and  
71 paleontological contexts with a large temporal range of action, providing the fact that  
72 mineralized tissues are preserved. However, inferring a TLE within mammalian communities  
73 relies on first order observations of Ca isotopic variability among predators and their preys.  
74 As highlighted in previous work, many uncertainties remain concerning the mechanisms  
75 behind fractionation processes as related to physiology versus environmental sources. As  
76 such, not all taxa are strictly following the theoretical isotopic/trophic clustering in the faunas  
77 studied so far. For some specific faunas and trophic niches, diet seems hard to constrain with  
78 Ca isotopes only (Reynard et al., 2010; Melin et al., 2014). Moreover, bone or enamel Ca  
79 isotope compositions sometime overlap between herbivores and predators, with herbivores  
80 occasionally exhibiting isotope compositions more  $^{44}\text{Ca}$ -depleted than predators from the  
81 same fauna (e.g. hippopotamidae, mammoths and cervidae; see Martin et al., 2017a, 2018;  
82 Dodat et al., 2021). This raises important questions about what can generate such issues, and  
83 highlights how critical it is for the accurate use of this proxy to reconcile the evidences of  
84 TLE with the occasional decoupling recorded between trophic level and Ca isotope  
85 compositions.

86 The isotopic offset between diet and bone which generates the TLE ( $\Delta^{44/42}\text{Ca}_{\text{diet-bone}}$ ) is  
87 relatively constant among mammal species with a value of  $-0.54 \pm 0.08 \text{ ‰}$  (2 standard error,  
88 20 individuals from 6 mammal species; reviewed in Tacail (2017)), despite resulting from the  
89 combination of numerous body Ca fluxes associated with Ca isotope fractionation (Skulan  
90 and DePaolo, 1999; Chu et al., 2006; Hirata et al., 2008; Tacail et al., 2014; Heuser et al.,  
91 2016; Tacail, 2017). The most impactful fluxes identified so far are the kidney Ca  
92 reabsorption from primary urines (Skulan et al., 2007; Heuser and Eisenhauer, 2010; Morgan

93 et al., 2012; Tacail et al., 2014; Channon et al., 2015; Heuser et al., 2016, 2019; Eisenhauer et  
94 al., 2019), the milk production and excretion (Chu et al., 2006; Reynard et al., 2010) and the  
95 bone mineralization (Skulan and DePaolo, 1999; Skulan et al., 2007; Heuser and Eisenhauer,  
96 2010; Reynard et al., 2010; Morgan et al., 2012; Channon et al., 2015), although the  
97 significance of this last has been recently questioned (Tacail, 2017; Tacail et al., 2020).  
98 Changing these fluxes, like during gestation, lactation (Ramberg Jr et al., 1970; Cross et al.,  
99 1995; Giesemann et al., 1998; Karlsson et al., 2001; Wysolmerski, 2002; Vanhouten and  
100 Wysolmerski, 2003; Gallego et al., 2006; Kovacs and Fuleihan, 2006; Tacail, 2017) or  
101 antlerogenesis (Mitchell et al., 1976; Muir et al., 1987a, 1987b), likely modify the Ca isotopic  
102 equilibrium of the organism, the resulting  $\Delta^{44/42}\text{Ca}_{\text{diet-bone}}$  offset, and could generate TLE  
103 discrepancies. Alternatively, the consumption of milk during nursing can also generate TLE  
104 discrepancies by changing the diet Ca isotope composition of non-weaned individuals  
105 compared to weaned individuals (Chu et al., 2006; Li et al., 2016, 2020; Tacail et al., 2017,  
106 2019). Finally, Ca enriched mineral supplementation such as with mineral licks and  
107 osteophagia, as well as the Ca isotopic variability inherent to plants (Holmden and Bélanger,  
108 2010; Gussone and Heuser, 2016; Schmitt, 2016; Moynier and Fujii, 2017; Martin et al.,  
109 2018; Griffith et al., 2020), are also able to blur the trophic clustering of Ca isotope  
110 compositions. The aim of this study is thus to investigate how these seven factors can affect  
111 bone and enamel Ca isotope compositions in modern animals, then to use this background to  
112 unravel a case study of TLE discrepancy previously documented.

113 We carried out the first part of this project by monitoring the bone and enamel Ca  
114 isotope compositions of a modern cervid population (red deer, *Cervus elaphus*), mainly  
115 originating from the Bauges Natural Regional Park (NRP), Alps, (Savoie, France). This  
116 modern population then served as a model to discuss TLE discrepancies, and more precisely

117 to discuss the case of the reindeers (*Rangifer tarandus*) from the Pleistocene locality of  
118 Jaurens (Corrèze, France). Martin et al. (2017a) showed that reindeers from this locality  
119 (dated between 32.6 to 29.7 kyr BP, Guérin et al. 1979) exhibit  $^{44}\text{Ca}$ -depleted compositions in  
120 tooth enamel down to a  $\delta^{44/42}\text{Ca}$  value of  $-1.75 \pm 0.09 \text{ ‰}$  (2 standard deviation.; 3 individuals).  
121 This is different from the Ca isotope compositions of the other herbivores of this locality, and  
122 closer from the one of lions and wolfs (Martin et al., 2017a). In accordance with the  
123 documented effects of nursing on the body Ca isotope composition of the young (Chu et al.,  
124 2006; Li et al., 2016, 2020; Tacail et al., 2017, 2019), Martin et al. (2017a) proposed that  
125 these negative  $\delta^{44/42}\text{Ca}$  values could result from the consumption of maternal milk by reindeers  
126 at the time when their analyzed molars were mineralizing (second molars, M2). Although this  
127 hypothesis is tempting, no direct evidence was available to prove that this phenomenon was  
128 responsible for the  $^{44}\text{Ca}$ -depleted isotope composition reported among Jaurens fossil cervids,  
129 leading to this new investigation.

130 To ensure the completion of our study it was necessary to assess at which degree the  
131 Ca isotope composition of bone and enamel are comparable. Previous studies found  
132 differences in  $\delta^{44/42}\text{Ca}$  values between bone and enamel or bone and enameloid (Heuser et al.,  
133 2011; Tacail et al., 2014; Martin et al., 2015, 2017a), but it was unclear whether this offset  
134 ( $\Delta^{44/42}\text{Ca}_{\text{bone-enamel}}$ ) was due to different Ca isotope fractionation coefficient during  
135 mineralization ( $\alpha_{\text{blood-bone}}$  and  $\alpha_{\text{blood-enamel}}$ ), to different mineralization timing, or to diagenesis.  
136 Our modern red deer population is free of diagenetic influence, and therefore, mineralization  
137 timings and differences between  $\alpha_{\text{blood-bone}}$  and  $\alpha_{\text{blood-enamel}}$  are the only factors affecting bone  
138 and enamel Ca isotopic differences. In other words, characterizing  $\alpha_{\text{blood-bone}}$  and  $\alpha_{\text{blood-enamel}}$  in  
139 red deer allow to accurately compare the different ontogenetic time periods recorded by these  
140 two tissues.

## 141 **2. Material and methods**

### 142 *2.1. Modern specimens*

143 We studied a total of 21 specimens of wild red deer of two age classes (subadult and  
144 adult) and sex (10 males, 11 females), coming from Bauges NRP, Alps, (Savoie, France,  
145 45.69 °N, 6.14 °E) and slaughtered during the hunting season in 2015 (between October and  
146 November) as part of the local hunting activity. In order to identify lactation, gestation and  
147 antlerogenesis effects on the Ca isotope composition of mineralized tissues, we analyzed and  
148 compared the bone Ca isotope composition of females and males. Our two age classes allow  
149 to distinguish specimens free of strong lactation, gestation and antlerogenesis effects (two  
150 years old, referred as subadult) from the others (aged of three years or more, referred as  
151 adult). Ages of the individuals were either known thanks to population monitoring or  
152 estimated based on tooth eruption and attrition stages (Brown and Chapman, 1991a, 1991b;  
153 table S1). The reproductive status of studied females was not directly monitored, but we know  
154 from observations of the OFB (Office Français de la Biodiversité) that in the red deer  
155 population of the Bauges NRP, 80 to 100 % of females aged of three years already gave birth  
156 at least once. Moreover, the OFB report that each year, about 80 % of the females aged of  
157 three years or more will have a fawn. We can refine this estimation as we know the body mass  
158 of studied specimens and that fertility is strongly related to body mass in cervids. Females are  
159 usually fertile when attaining 80 % of the adult body mass (Albon et al., 1986; Pellerin et al.,  
160 2014) and are around 30 % heavier at the end of autumn if they did not gave birth to a fawn  
161 earlier in the year (Mitchell et al., 1976; Clutton-Brock et al., 1982). These data allow to  
162 identify females which were too puny to be fertile, and females which were suspiciously too  
163 fat to have nursed a fawn recently. At the light of these data and knowing that the Bauges  
164 NRP deer population breed quite actively, we can confidently assume that adult females



165 weighting between 65 and 105 kg have given birth to a fawn during the 2015 birth season  
166 (table S1).

167 Bone samples were collected from mandibles, previously manually cleaned and boiled  
168 prior to be integrated to the collection of the PALEVOPRIM laboratory (UMR CNRS 7262 -  
169 University of Poitiers, France). For each mandible, bone sample powder was collected few  
170 centimeters under the second molar, with the help of a handheld drill (8200 Dremel equipped  
171 with a tungsten steel solid carbide bit). In order to remove any trace of dirt or other  
172 environmental contaminants, the first layer of bone surface was removed with the drill then  
173 cleaned with pure ethanol prior to sampling. Between 0.4 and 0.7 mg of bone powder were  
174 sampled and weighted prior to chemical preparation.

175 Along with bone sampling and in order to investigate intra-tissue and inter-tissue  
176  $\delta^{44/42}\text{Ca}$  variability, we selected two specimens for serial enamel micro-sampling. The first is  
177 an adult male with premolars P2, P3, P4, and molars M1, M2, M3 fully emerged and  
178 moderately worn (specimen ID number: UP-15CE5672, lab name: AB). The second is a  
179 juvenile female with deciduous premolar DP2, DP3, DP4, and molars M1, M2 fully emerged  
180 and with an erupting M3 in ongoing mineralization (specimen ID number: UP-15CE3734, lab  
181 name: JVB). The serial micro-samplings performed on these specimens provide snapshots of  
182 the enamel Ca isotope composition at different ages, depending on when each enamel zone  
183 mineralized. This ultimately allows to identify isotopic anomalies produced by milk  
184 consumption, osteophagia, mineral licks or occasional consumption of  $^{44}\text{Ca}$ -depleted plants.  
185 These deer specimens (AB and JVB), also had some plant leftovers trapped between their  
186 teeth. We collected these rests for elemental concentration analyses.

187 To assess the effect of antlerogenesis and antler consumption we selected an adult  
188 male red deer preserved with its skull, mandible and antlers in the collections of the  
189 Confluence Museum (Lyon, France). This specimen (ID number: MHNL-50002207, lab  
190 name: SPB) is of unknown European origin and has been sampled following the same bone  
191 sampling procedure than specimens from Bauges NRP. One sample has been retrieved from  
192 the mandible, the other three were retrieved on the main beam of the right antler, respectively  
193 at the base, the middle and the top of the antler.

## 194 *2.2. Fossil specimens*

195 In order to study the trophic position of reindeer from the Late Pleistocene Jaurens  
196 fauna and their peculiar Ca isotope composition, we selected four specimens to carry out  
197 serial enamel micro-sampling. We focused our efforts on enamel sampling instead of bones in  
198 order to limit diagenesis influence. All specimens are part of the paleontological collections of  
199 the Laboratory of Geology of Lyon (LGL-TPE, France). This includes two mandibles (one  
200 adult and one juvenile) with their associated teeth, and two isolated teeth (lower M1 and a  
201 lower DP4) from two different individuals. One of the two mandibles comes from an adult  
202 specimen with the teeth P2, P3, P4, M1, M2, M3 fully emerged and with significant tooth  
203 wear on the M1 (specimen ID number: FSL 451.409, lab name: AJ). The second mandible  
204 comes from a juvenile specimen with the teeth DP2, DP3, DP4, M1 fully emerged and with  
205 the M2 erupting (specimen ID number: FSL 451.389, lab name: JVJ). The isolated teeth are a  
206 lower left DP4 (specimen ID number: FSL 451.398, lab name: ISO DP4) and lower right M1  
207 (specimen ID number: FSL 451.384, lab name: ISO M1), both with a minimal wear level. The  
208 lessons learned from modern specimens allow to critically discuss our new and previous  
209 (Martin et al., 2017a) enamel Ca isotope data collected on fossil reindeers from Jaurens.

210 2.3. *Micro-sampling*

211 We designed two different procedures of serial micro-sampling. For both we use a  
212 computer-assisted micro drill device (MicroMill), allowing the sampling of 80-120  $\mu\text{g}$   
213 hydroxylapatite by drilling holes of 350–400  $\mu\text{m}$  wide and about 400  $\mu\text{m}$  depth. Teeth  
214 selected for micro-sampling were serially sampled by micro-drilling on the enamel between  
215 the apex (i.e. the top) and the neck of the tooth (i.e. the basal most enamel zone), along the  
216 growth axis of the best preserved cusp of the lingual face. The apex is mineralizing first  
217 whereas the enamel close to the neck is the last part of the enamel to mineralize. This  
218 sampling thus maximizes the studied intra-tooth time window and allows a high temporal  
219 resolution. When possible we performed serial micro-sampling using a “edge-drilling  
220 procedure”. In this case, the tooth (either isolated or extracted from a mandible) was cut along  
221 the growth axis in the central part of the cusp by using a Buehler IsoMet Low Speed precision  
222 sectioning saw with a diamond-studded circular saw blade. The edge of the enamel was then  
223 polished using sandpaper with decreasing grain sizes prior to perform the micro sampling.  
224 Sampling zones were located close to the enamel-dentine junction (EDJ) in order to minimize  
225 the temporal lag between the mineralization of appositional structures and enamel maturation  
226 (Blumenthal et al., 2014; Green et al., 2017; Trayler and Kohn, 2017; Müller et al., 2019).  
227 Alternatively, when extracting and cutting teeth was impossible or when the targeted spatial  
228 sampling resolution was sufficiently low, enamel has been micro-drilled from the outer side  
229 (“outer-drilling procedure”). For this procedure, the one or two first hundreds of  $\mu\text{m}$  of drilled  
230 enamel were not collected, in order to collect enamel relatively close to the EDJ similarly as  
231 in the edge-drilling procedure. The choice of procedure is reported in table S1 and S2.

232 *2.4. Thin section and enamel age model*

233 We were allowed to make thin sections on the micro sampled surface of the M1 of  
234 AB, JVB (red deer, Bauges) and ISO M1 (reindeer, Jaurens). Teeth were then sliced and  
235 polished in order to obtain 100  $\mu\text{m}$  thick sections. Observations in transmitted light  
236 microscopy failed to reveal neonatal lines within the enamel layers of the three M1 (AB, JVB,  
237 ISO M1), a structure observed in early mineralizing teeth of humans and other mammals that  
238 would mark birth (Klevezal and Mina, 1995; Zanolli et al., 2011; Dean et al., 2019). The age  
239 model necessary to anchor our enamel  $\delta^{44/42}\text{Ca}$  data was alternatively based on general  
240 observations made on tooth mineralization timing of red deer (Brown and Chapman, 1991b).  
241 Such data were not available for reindeer, but similarities between red deer and reindeer teeth  
242 eruption timings (Miller, 1972; Brown and Chapman, 1991b; Azorit et al., 2002) allow to use  
243 red deer data to build a coarse reindeer age model. As teeth are subject to wear, we spatially  
244 anchored our age model on the neck of teeth. The mean mineralization age of each enamel  
245  $\delta^{44/42}\text{Ca}$  data point is then estimated based on the distance between the sampling zone and the  
246 neck of the tooth, on corresponding mineralization timings (Brown and Chapman, 1991b),  
247 and on the estimated full height of unworn teeth measured on young specimens. This method  
248 assumes a constant enamel mineralization rate along the tooth growth axis and inside tooth  
249 families. This method is thus not adapted to discuss inter-individual or intra-tooth differences  
250 in tooth mineralization rates and timings but allow for a fairly good estimation considering  
251 that enamel micro-samples average a body isotopic record spanning over a month to several  
252 months (further discussed in appendix). For studied red deers, unworn teeth displayed similar  
253 crown heights between specimens. Reindeer specimens, however, had unworn molars and  
254 premolars approximately 15 % smaller than red deer, which has been considered in our age  
255 model.

256 *2.5. Sample dissolution and ion chromatography*

257 Immediately after sampling, bone and tooth samples were transferred in Teflon  
258 beakers. All further manipulations have been done exclusively in a clean lab or under a  
259 laminar flux hood. Modern bone samples were dried with 500  $\mu\text{L}$  of pure ethanol evaporated  
260 at 70  $^{\circ}\text{C}$ . No attempt of leaching procedures has been carried out for fossil enamel samples, as  
261 previous Ca isotope analyses demonstrated no isotopic differences between leached and non-  
262 leached enamel in Jaurens samples (Martin et al., 2017a). All samples were dissolved using a  
263 mix of 1 ml of 15 M ultrapure nitric acid ( $\text{HNO}_3$ ) and 300  $\mu\text{L}$  of ultrapure hydrogen peroxide  
264 (30 %). Beakers were left closed at ambient temperature for 1h, then were heated at 130  $^{\circ}\text{C}$   
265 during 1 to 2 h more with regular degassing of nitrous fumes. When production of nitrous  
266 fumes became limited, 300  $\mu\text{L}$  of ultrapure hydrogen peroxide (30 %) were added and  
267 samples were left to dry down at 90  $^{\circ}\text{C}$  for few hours. The presence of organic matter was  
268 then tested using 100  $\mu\text{L}$  of ultrapure hydrogen peroxide (30 %). No effervescence was  
269 detected for any of the samples and solutions were thus left to dry down at 90  $^{\circ}\text{C}$ . Samples  
270 selected for elemental concentration analyses were dissolved in 0.5 M ultrapure  $\text{HNO}_3$  then  
271 split. A fraction of the solution was reserved for concentration analyses and the rest was dried  
272 down at 90  $^{\circ}\text{C}$ . These dried fractions and the samples not selected for concentration analyses  
273 were kept for Ca isotope analyses, dissolved in 300-500  $\mu\text{L}$  of 6M ultrapure hydrochloric acid  
274 ( $\text{HCl}$ ) and dried down at 90  $^{\circ}\text{C}$ .

275 The chromatography procedure used for Ca chemical purification is derived from  
276 Tacail et al. (2014). This consist in a double column chromatography, starting with an elution  
277 on AG 50WX-12 resin with ultrapure  $\text{HCl}$ , and followed by an elution on Eichrom Sr-specific  
278 resin with an ultrapure  $\text{HNO}_3$  medium. When high level of iron was suspected (e.g. fossil  
279 samples) a third column chromatography was performed, using 1 mL of AG1 X8 resin and

280 following a procedure derived from Tacail et al. (2014). Blanks have been realized along the  
281 digestion and the chromatography, including total procedural blanks which have undergone  
282 all the steps previously described and chromatography blanks.

### 283 2.6. Analytical procedures and nomenclature

284 For more clarity within this paper, the n notation refers to the number of samples or  
285 specimens whereas the n\* notation specifically refers to number of measurement replicates.  
286 The “s.d.” notation refers to “standard deviation”, whereas “s.e.” refers to “standard error”.  
287 Concentrations of major and trace elements were measured respectively on an inductively  
288 coupled plasma atomic emission spectrometer (ICP-AES) (ICAP 7400 Series, Thermo  
289 Scientific) and on an inductively coupled plasma mass spectrometer (ICP-MS) (ICAP-Q,  
290 Thermo Scientific). The reliability of measurements has been controlled through a set of  
291 blanks and reference material (SRM1486), and by replicating measures to n\* = 2 for each  
292 sample.

293 We measured the Ca isotope ratios ( $^{44}\text{Ca}/^{42}\text{Ca}$ ) using a multi-collector inductively  
294 coupled plasma mass spectrometer (MC-ICP-MS, Neptune Plus, Thermo Scientific)  
295 following the method described in Tacail et al. (2014). Prior Ca isotope analyses, Ca purified  
296 samples were dissolved and diluted in 0.05M HNO<sub>3</sub> in order to set the Ca concentration at  
297 1.25 mg.L<sup>-1</sup>. This concentration matches that of the ICP Ca Lyon, our in-house bracketing  
298 reference material made of Specpure Ca plasma standard solution (Alfa Aesar) and described  
299 in previous studies (Tacail et al., 2014, 2017; Martin et al., 2015, 2017a). Unless explicit  
300 mention, the Ca isotope compositions reported in this article are all expressed as  $\delta^{44/42}\text{Ca}$   
301 relatively to ICP Ca Lyon using the following formula:

$$302 \quad \delta^{44/42}\text{Ca} = ((^{44}\text{Ca}/^{42}\text{Ca})_{\text{sample}} / (^{44}\text{Ca}/^{42}\text{Ca})_{\text{ICP Ca Lyon}}) - 1) \times 1000$$

303

304 For easing comparisons with studies using other reference materials,  $\delta^{44/42}\text{Ca}_{\text{ICP Ca Lyon}}$  values  
 305 are converted to  $\delta^{44/42}\text{Ca}_{\text{SRM915a}}$  in our tables and figures. Based on 71 measures synthesized in  
 306 the appendix of Martin et al. (2018), we converted  $\delta^{44/42}\text{Ca}_{\text{ICP Ca Lyon}}$  values to  $\delta^{44/42}\text{Ca}_{\text{SRM915a}}$   
 307 values by adding +0.518‰ to  $\delta^{44/42}\text{Ca}_{\text{ICP Ca Lyon}}$  values. To express a difference of  $\delta^{44/42}\text{Ca}$  value  
 308 between two Ca reservoirs we use the  $\Delta$  notation based on the following formula:

$$309 \quad \Delta_{x-y} = \delta_x - \delta_y$$

310 Where x and y are different Ca reservoirs. Secondary reference materials of different matrix  
 311 and documented Ca isotope composition have been used to ensure the accuracy of our  
 312 analytical procedure and chemical purifications. The SRM1486 cow bone meal reference  
 313 material (NIST) was used in that purpose, as well as the IAPSO sea water (OSIL). The Ca  
 314 concentration of the blanks have also been measured with the Neptune Plus. Sample Ca  
 315 isotope compositions are considered different when their  $\delta^{44/42}\text{Ca}$  mean value ( $\pm 2$  s.e.) do not  
 316 overlap. Groups of  $\delta^{44/42}\text{Ca}$  mean values are compared using Wilcoxon rank-sum tests.

### 317 **3. Results**

#### 318 *3.1. Trueness and precision*

319 Chromatography and total blanks display a maximum of 70 ng of Ca. This is several  
 320 thousand times less than the amount of Ca in our macro-samples (e.g. bone samples) which is  
 321 thus negligible. Most of our micro-samples (i.e. collected from spatial micro-sampling)  
 322 contained more than 6250 ng of Ca, and in the worst cases about 3800 ng of Ca. In this case  
 323 Ca from blanks is not completely negligible but its effect can be considered minimal. Indeed,  
 324 a simple mass balance calculation show that even a contamination with environmental Ca of  
 325 extreme isotopic composition (close to seawater  $\approx 0.41$  ‰; Martin et al. (2015)) affecting an  
 326 extremely  $^{44}\text{Ca}$ -depleted sample (e.g.  $\delta^{44/42}\text{Ca} = -2.00$  ‰) with 3800 ng of Ca would only

327 generate a +0.04 ‰ difference. This unlikely +0.04 ‰ correspond to the maximum of  
328 contamination effect possibly expected with our blank levels for the smallest of our micro  
329 samples. Such effects can thus be neglected considering the order of magnitude of inter-  
330 sample differences discussed below.

331 The complete Ca isotope dataset of this study include 104 samples and reference  
332 materials for a total of 358 accurate measurements. The correlation between  $\delta^{43/42}\text{Ca}$  and  
333  $\delta^{44/42}\text{Ca}$  values of each of these samples/reference materials follow the mass dependent  
334 relation expected for Ca isotope ratios (figure 1), with a slope value of  $0.508 \pm 0.010$  (2 s.e)  
335 an intercept of  $0.006 \pm 0.015$  (2 s.e) and a  $R^2 = 0.99$  (p-value < 0.001). This demonstrates that  
336 no mass independent fractionation or mass specific interference has affected our  
337 measurements. Along with our different sessions of analysis, the SRM1486 exhibited a mean  
338  $\delta^{44/42}\text{Ca}$  of  $-0.99 \pm 0.13$  ‰ (2 s.d. inter-session, n = 8 sessions) with a mean intra-session 2 s.d.  
339 of 0.08 ‰ (n = 88 measurements). Our other secondary reference material, the IAPSO  
340 exhibited a mean  $\delta^{44/42}\text{Ca}$  of  $+0.38 \pm 0.12$  ‰ (2 s.d. inter-session, n = 5 sessions) with a mean  
341 intra-session 2 s.d. of 0.06 ‰ (n = 14 measurements). These results are both in the range of  
342 previously published data (table S3) for the SRM1486 (Heuser and Eisenhauer, 2008; Tacail  
343 et al., 2016, 2017; Martin et al., 2018) and the IAPSO (Tacail et al., 2014; Martin et al.,  
344 2015). By considering all the measurements of samples and reference materials (n = 107), the  
345 mean intra-sample reproducibility was of  $\pm 0.07$  ‰ (2 s.d., n = 358 measurements).

### 346 3.2. Bone data among modern cervids

347 The bone sample set from Bauges NRP display a range of  $\delta^{44/42}\text{Ca}$  between  $-1.62 \pm$   
348  $0.19$  ‰ (2 s.d., n\* = 3) and  $-1.22 \pm 0.04$  ‰ (2 s.d., n\* = 2), with a mean 2 s.d. of 0.09 ‰.  
349 Females red deer have a mean bone  $\delta^{44/42}\text{Ca}$  value of  $-1.36 \pm 0.24$  ‰ (2 s.d., n = 11), and  
350 males a mean bone  $\delta^{44/42}\text{Ca}$  value of  $-1.41 \pm 0.27$  ‰ (2 s.d., n = 10). The  $\delta^{44/42}\text{Ca}$  values of



351 female individuals are statistically indistinguishable from males when considering all age  
352 classes together (Wilcoxon rank-sum test, p-value = 0.3494), but this change when  
353 considering adult specimens only (Wilcoxon rank-sum test, p-value = 0.0499). Isolating  
354 females who gave birth during the last birth season from the other females allows for an even  
355 clearer distinction (figure 2). These six females (later referred as lactating hinds or females)  
356 display bone  $\delta^{44/42}\text{Ca}$  values higher of  $+0.23 \pm <0.01$  ‰ (95 % confidence interval) compared  
357 to the two adult females who did not reproduce recently (later referred as yeld hinds), and  
358 differ significantly from adult males (Wilcoxon rank-sum test, p-value  $< 0.01$ ; figure 3) with a  
359 mean bone  $\delta^{44/42}\text{Ca}$  value higher of  $+0.17 \pm 0.10$  ‰ (95 % confidence interval). The three  
360 subadult females display a range of bone  $\delta^{44/42}\text{Ca}$  values which overlap with both lactating and  
361 yeld adult hinds, with the heaviest subadult females displaying the highest bone  $\delta^{44/42}\text{Ca}$   
362 values. Finally, the correlation between adult male body mass and bone  $\delta^{44/42}\text{Ca}$  values is  
363 virtually absent ( $R = -0.29$ , p-value = 0.49,  $n = 8$ ). We can make no distinction between bone  
364  $\delta^{44/42}\text{Ca}$  values of adult males and subadult males (Wilcoxon rank-sum test, p-value = 0.18) or  
365 between adult males and subadult or yeld females (Wilcoxon rank-sum test, p-value = 0.62).

366 The SPB specimen displays a mandible bone  $\delta^{44/42}\text{Ca}$  value of  $-1.62 \pm 0.04$  ‰ (2 s.d.,  
367  $n^* = 3$ ), whereas the bone of the antler displays  $\delta^{44/42}\text{Ca}$  values of  $-1.43 \pm 0.02$  ‰ (2 s.d.,  $n^* =$   
368 4) at the base,  $-1.49 \pm 0.06$  ‰ (2 s.d.,  $n^* = 3$ ) in the middle and  $-1.38 \pm 0.06$  ‰ (2 s.d.,  $n^* = 4$ )  
369 at the top of the right antler (figure 4). Each of the antler  $\delta^{44/42}\text{Ca}$  values is significantly higher  
370 from that of the mandible by 0.13 ‰ or more. Calcium and phosphorus concentrations  
371 decrease from the base to the tip of the antlers, whereas magnesium reaches its maximum  
372 concentration in the middle part of the antler (table S4).

## 373 3.3. Enamel micro-samples

374 Enamel and bone Ca isotope data of specimen AB (adult male) and JVB (juvenile  
375 female) are reported in figure 5. Among these individuals, a majority of enamel  $\delta^{44/42}\text{Ca}$  values  
376 of most adult parts of M3 and M2 teeth are undistinguishable from bone, whereas the DP4  
377 (when present) and the early mineralizing part (next to the crown apex) of the M1 display  
378  $\delta^{44/42}\text{Ca}$  values which are -0.23 ‰ to -0.37 ‰ lower than bones. A similar difference is  
379 observed within the M1 of the AB specimen, with early mineralizing parts exhibiting a  
380  $\delta^{44/42}\text{Ca}$  value -0.22 ‰ lower than late mineralizing parts. Plant remains found between tooth  
381 cusps from AB and JVB display a Ca concentration of 1.83 wt% and 0.99 wt%, respectively.  
382 The complete  $\delta^{44/42}\text{Ca}$  dataset of the specimens from the Bauges NRP is reported in table S1.

383 Enamel  $\delta^{44/42}\text{Ca}$  values of fossil reindeer (figure 6) range between  $-1.21 \pm 0.04$  ‰ (2  
384 s.d.,  $n^* = 3$ ) and  $-2.03 \pm 0.08$  ‰ (2 s.d.,  $n^* = 2$ ). As for studied red deer, specimens with  
385 unworn M1 (JVJ and ISO M1) exhibit an important change of  $\delta^{44/42}\text{Ca}$  values between early  
386 and late mineralizing enamel. The earliest mineralizing part of the M1 display a  $\delta^{44/42}\text{Ca}$  value  
387 lower by -0.82 ‰ for JVJ and by -0.47 ‰ for ISO M1 compared to last mineralizing part of  
388 the M1. The enamel of the DP4 of JVJ display a  $\delta^{44/42}\text{Ca}$  value of  $-1.94 \pm 0.06$  ‰ (2 s.d.,  $n =$   
389 3), undistinguishable from that of the earliest mineralizing part of its M1 ( $-2.03 \pm 0.08$  ‰, 2  
390 s.d.,  $n^* = 2$ ). Fluctuations of  $\delta^{44/42}\text{Ca}$  values during the adult life of reindeer are also observed  
391 within the M3 and the P4 of the AJ specimen. The mean  $\delta^{44/42}\text{Ca}$  value measured on these two  
392 teeth is  $-1.56 \pm 0.19$  ‰ (2 s.d.,  $n = 3$  for each tooth) with a total range of 0.22 ‰. The  
393 complete  $\delta^{44/42}\text{Ca}$  dataset of the specimens from Jaurens is reported in table S2.

394 All three DP4 teeth display a pattern of low  $\delta^{44/42}\text{Ca}$  values, relatively stable from the  
395 apex to the neck ( $\Delta_{\text{max-min}} = 0.11$  ‰; intra-teeth 2 s.d. = 0.11 ‰,  $n = 7$ ). The M1 teeth display a  
396 different pattern, with AB, JVJ and ISO M1 specimens exhibiting a high amplitude change

397 from low to high  $\delta^{44/42}\text{Ca}$  values from the apex to the neck ( $\Delta_{\text{max-min}} = 0.50 \text{ ‰}$ ; intra-teeth 2 s.d.  
 398 =  $0.35 \text{ ‰}$ ,  $n = 3$ ). The M1 of JVB displays more stable low  $\delta^{44/42}\text{Ca}$  values ( $\Delta_{\text{max-min}} = 0.17 \text{ ‰}$ ;  
 399 intra-teeth 2 s.d. =  $0.12 \text{ ‰}$ ,  $n = 7$ ), whereas the M1 of AJ displays stable  $\delta^{44/42}\text{Ca}$  values close  
 400 to its M2 and M3  $\delta^{44/42}\text{Ca}$  values ( $\Delta_{\text{max-min}} = 0.11 \text{ ‰}$ ; intra-teeth 2 s.d. =  $0.12 \text{ ‰}$ ,  $n = 3$ ).

#### 401 4. Discussion

##### 402 4.1 Comparability of bone and enamel Ca isotope composition

403 We observe some offsets of  $\delta^{44/42}\text{Ca}$  bone and enamel values in the M2 and M3 tooth  
 404 of AB and JVB specimens (figure 5), but these offsets tend to be rarer after 5-6 months. The  
 405 fact that the late mineralizing enamel of the M2 and M3 of red deer specimens AB and JVB  
 406 display a  $\delta^{44/42}\text{Ca}$  value predominantly identical to their bones (figure 5), suggest that a similar  
 407 Ca isotope fractionation occur during bone and enamel mineralization (i.e.  $\alpha_{\text{blood-bone}} \approx \alpha_{\text{blood-}}$   
 408  $\text{enamel}$  and  $\alpha_{\text{diet-bone}} \approx \alpha_{\text{diet-enamel}}$ ), despite that different cellular processes are involved. A similar  
 409 suggestion arises from human populations who exhibit M3 teeth with a  $\Delta^{44/42}\text{Ca}_{\text{diet-enamel}}$  value  
 410 similar to the general mammal  $\Delta^{44/42}\text{Ca}_{\text{diet-bone}}$  (Tacail et al., 2017), which suggest that this  
 411 could be a general feature among mammals or even vertebrates. These data consequently  
 412 support that  $\Delta^{44/42}\text{Ca}_{\text{bone-enamel}}$  offset, when existing (Heuser et al., 2011; Tacail et al., 2014;  
 413 Martin et al., 2015, 2017a), are more likely caused by diagenetic alteration (for fossil tissues),  
 414 or by the different mineralization timings of enamel and bone. Indeed, in contexts of variable  
 415 body Ca isotope composition (e.g. forced by seasonal dietary variations), these different  
 416 mineralization timings generate different bone and enamel  $\delta^{44/42}\text{Ca}$  values, with bone sections  
 417 averaging years of body Ca isotope compositions and enamel micro-samples reflecting week  
 418 to month periods (see appendix section for further discussion of the length of these  
 419 mineralization periods).

420 4.2 Physiological control on  $\delta^{44/42}\text{Ca}$  values in adult tissues

## 421 4.2.1 Gestation effects

422 In the red deer population from Bauges NRP, adult females who recently gave birth  
423 (referred as lactating hinds) display a mean bone  $\delta^{44/42}\text{Ca}$  value of  $+0.17 \pm 0.10$  ‰ (95 %  
424 confidence interval) higher than adult males (figure 3). This is similar to what was previously  
425 reported for domestic sheep (Reynard et al., 2010), in which females (n = 8) displayed a bone  
426  $\delta^{44/42}\text{Ca}$  value significantly higher of  $+0.14 \pm 0.08$  ‰ (95 % confidence interval) compared to  
427 males (n = 16). The two factors pointed to be the cause of this sexual driven difference in  
428 sheep were the accretion of bone during gestation and the excretion of milk (Reynard et al.,  
429 2010), as only these two Ca fluxes were thought to be associated with Ca isotope fractionation  
430 at this time. However, the very low enamel  $\delta^{44/42}\text{Ca}$  values we record in cervid teeth  
431 mineralizing *in utero* (DP4, early M1, figure 5 and 6) suggest that during gestation a mother  
432 will preferentially transfer light Ca isotopes through placental Ca transfer. This is also  
433 observed in human deciduous teeth (Tacail et al., 2017, 2019), although recent data point out  
434 that it could be representative of the last stage of gestation only (Li et al., 2020). Such  
435 trapping of isotopically light Ca by the foetus would have comparatively enriched mother  
436 tissues in heavy Ca isotopes (including mineralizing bone or enamel). The most simplistic box  
437 model of gestation (a 2 box model with a  $\Delta^{44/42}\text{Ca}_{\text{fawn-hind}}$  of -0.25‰ and a hind giving 10% of  
438 her Ca to her fawn) gives a  $\delta^{44/42}\text{Ca}$  shift of +0.02 to +0.03 ‰ for the hind, but it has to be  
439 noted that this model is very simplistic and amplifies the shift compared to reality (notably by  
440 neglecting Ca transfers from the foetus to the hind and the Ca intake of the hind). Among  
441 other changes, gestation also triggers higher Ca urinary excretions (Giesemann et al., 1998;  
442 Kovacs and Fuleihan, 2006; Reynard et al., 2010), a Ca flux which contributes to lower blood  
443  $\delta^{44/42}\text{Ca}$  values by preferentially exporting heavy Ca isotopes in urines (Skulan et al., 2007;

444 Heuser and Eisenhauer, 2010; Morgan et al., 2012; Tacail et al., 2014; Channon et al., 2015;  
445 Heuser et al., 2016, 2019; Tacail, 2017; Eisenhauer et al., 2019). Thus, the consequences of  
446 gestation have opposite influences on blood Ca isotope composition, and therefore limit the  
447 record of a gestation signal in bone and enamel. Moreover, the recent questioning about the  
448  $\alpha_{\text{blood-bone}}$  amplitude (Tacail, 2017; Tacail et al., 2020) also questions the base of the bone  
449 accretion effect. Further investigations are necessary on this topic but at the moment these  
450 sparse data tend to demonstrate that gestation has a weak to absent effect on body Ca isotope  
451 compositions, and that bone differences between males and females recorded in red deer (this  
452 study) and sheep (Reynard et al., 2010) have another origin. Similarly, nothing suggests that  
453 gestation effects could significantly disrupt the trophic and isotopic clustering of adult bone  
454 and enamel Ca isotope compositions.

#### 455 *4.2.2 Lactation effects*

456 The amount of Ca provided by the hind to its fawn during the 3 to 8 months of nursing  
457 is huge, as a fawn grows to about the half of the hind body mass between its birth and  
458 weaning (table 1; table S1; Jones et al., 2009; Mitchell et al., 1976). Comparatively, a juvenile  
459 red deer usually weights about 8 kg at birth (Mitchell et al., 1976; Jones et al., 2009) which  
460 represents about 8.6 % of the mean body mass of adult hinds from our dataset (table S1) and  
461 consequently implies far less Ca transfers from the hind to the fawn than lactation does. As  
462 milk is very depleted in heavy Ca isotopes ( $\Delta^{44/42}\text{Ca}_{\text{milk-diet}} = -0.6\text{‰}$ ; Chu et al., 2006; Gussone  
463 and Heuser, 2016; Heuser, 2016; Tacail, 2017), its excretion can lead to enrich lactating  
464 females in Ca heavy isotopes (Reynard et al., 2010). Along with important Ca excretion  
465 through milk, lactating mammals are subject to higher absorption in the digestive tract, to  
466 bone loss and to changes in Ca urinary excretion (Ramberg Jr et al., 1970; Cross et al., 1995;  
467 Giesemann et al., 1998; Karlsson et al., 2001; Wysolmerski, 2002; Vanhouten and

468 Wysolmerski, 2003; Kovacs and Fuleihan, 2006; Tacail, 2017). However, such Ca flux  
469 changes likely secondarily affect the lactation signal, as these changes stay minimal compared  
470 to the order of magnitude of milk excretion. The lactation should therefore be characterized  
471 by higher body  $\delta^{44/42}\text{Ca}$  values in hinds, including within their bones if the nursing lasts for  
472 several months (see appendix). In this context, the high bone  $\delta^{44/42}\text{Ca}$  values reported in  
473 lactating hinds (figure 2 and 3) seems very compatible with the manifestation of a lactation  
474 effect, similarly to what is observed for domestic sheep (Reynard et al., 2010). The important  
475 residence time of Ca in bones certainly heavily damps this lactation signal (see appendix),  
476 although the extensive bone remodeling and bone losses usually recorded during lactation  
477 decreases this residence time and improves the potential of the signal to be recorded  
478 (Giesemann et al., 1998; Vanhouten and Wysolmerski, 2003; Kovacs and Fuleihan, 2006).  
479 Looking at subadult hinds for such a signal is more difficult, as their reproductive status is  
480 challenging to assess and that only about 50 % gave birth to fawns at two years according to  
481 OFB monitoring in Bauges NRP. However, higher body mass also suggests higher chance  
482 that they gave birth to a fawn during the last birth season (Mitchell et al., 1976; Clutton-Brock  
483 et al., 1982; Albon et al., 1986; Pellerin et al., 2014). Thus, the fact that bone  $\delta^{44/42}\text{Ca}$  values of  
484 subadult females overlap with both lactating and yield adult hinds suggest that this group  
485 includes both nulliparous and primiparous females (figure 3). This is also consistent with the  
486 fact that the heaviest subadult female displays the highest  $\delta^{44/42}\text{Ca}$  values, suggesting that this  
487 specimen gave birth to a fawn during the last birth season.

488 Interestingly, the female with the highest body mass of our dataset displays lower bone  
489  $\delta^{44/42}\text{Ca}$  values despite having an age and body mass suggesting lactating periods in previous  
490 birth seasons, as high body mass mean higher reproduction chances (Albon et al., 1986;  
491 Pellerin et al., 2014). This suggests that skeletal Ca turnover is intense enough to conceal

492 lactation signals from one year to another in this species, at least within the cortical part of the  
493 dentary bone (the bone part analyzed in this study). We lack precise data about bone  
494 remodeling rate for red deer dentary bone. However, this fast Ca turnover seems odd  
495 considering that the total skeleton would need about 9 years to remove 75 % of a lactation  
496 signal (see box model described in appendix). The post-lactation bone accretion and the  
497 relatively small male/female  $\delta^{44/42}\text{Ca}$  difference observed so far might help to achieve a  
498 quicker concealing of the lactation signal, but further experiments are necessary to confirm  
499 this dynamic as only one individual suggests this tendency. If bone Ca isotope composition  
500 proves to be that dynamic, the time interval between last lactation and death, as well as the  
501 time interval between consecutive lactations might be critical to preserve a lactation signal  
502 within bone Ca isotope composition. Nevertheless, the amount of produced milk, the duration  
503 of lactation periods and the size of the skeleton Ca reservoir also likely modulate this sex  
504 driven Ca isotopic difference among mammal species. Those factors are probably a key to  
505 explain why human populations studied by Reynard et al. (2010, 2013) display non-  
506 significant isotopic clustering between sexes, along with the diversity of possible food sources  
507 which characterize humans. Such lactation signal is in theory less dampened in enamel than in  
508 bones (see appendix). However, looking for these signals in adult teeth of red deer females  
509 seems challenging, as the enamel of the last tooth to mineralize (i.e. the M3) has generally  
510 completed its mineralization around 26 months (Brown and Chapman, 1991b), while only  
511 about half of two-year-old females are primiparous. We cannot be certain of that concerning  
512 the reindeer population of Jaurens. However, our data suggest that any record of a lactation  
513 signal within their enamel would result in higher enamel  $\delta^{44/42}\text{Ca}$  values, whereas these  
514 reindeers exhibit suspiciously low  $\delta^{44/42}\text{Ca}$  values. We thus conclude that lactation effects on

515 body Ca isotope composition have to be considered when studying mammal populations but  
516 cannot be invoked to explain anomalously low bone or enamel  $\delta^{44/42}\text{Ca}$  values.

#### 517 4.2.3 Antlerogenesis effects and antler records

518 We report the first comparison between Ca isotope compositions of antlers and the rest  
519 of the skeleton (figure 4). This pilot investigation highlights that antlers display  $\delta^{44/42}\text{Ca}$  values  
520 significantly higher than the rest of the skeleton. As for enamel and bones, the key is to assess  
521 whether this difference is the result from differences in Ca isotope fractionation coefficients at  
522 mineralization or the result of a different mineralization timing. These data call for further  
523 studies, as comparing antlers with bone and enamel could add an additional dimension for  
524 studying cervid life history traits using Ca isotopes, allowing to further investigate diet  
525 seasonality, for example.

526 With the only data presented in figure 4, it seems that antlers could preferentially trap  
527 heavy Ca isotopes from blood, although physiological processes generally favor light Ca  
528 isotopes (Tacail, 2017). If further confirmed, this would indicate that antlerogenesis could  
529 lower body Ca isotope composition. Indeed, antlers act primarily as a Ca sink working  
530 similarly as lactation and gestation by isolating Ca from the rest of the body, although antlers  
531 are also subject to bone remodeling (Bélanger et al., 1967; Muir et al., 1987a; Rolf and  
532 Enderle, 1999). However, the fact that lactation proved to have a relatively tenuous influence  
533 on bone  $\delta^{44/42}\text{Ca}$  values, despite involving far bigger Ca fluxes and Ca isotope fractionation  
534 coefficients than antlerogenesis (Mitchell et al., 1976; Muir et al., 1987a, 1987b; Harris et al.,  
535 2002; Thomas and Barry, 2005; Li, 2013), suggests that antlerogenesis will not be detectable  
536 within the skeleton Ca isotope composition. This is supported by the complete overlap we  
537 observe between male red deer, yeld and immature hinds bone  $\delta^{44/42}\text{Ca}$  values (figure 3). An  
538 overlap which occurs despite the fact that studied specimens have been slaughtered just when



539 the antlers of males finished their growth (Mitchell et al., 1976), so just when antlerogenesis  
540 could had a strong influence on skeleton Ca isotope composition. Although further tests are  
541 necessary to prove that enamel stay unaffected too, the end of enamel mineralization occurs  
542 before large antlers can grow (Kruuk et al., 2002; Thomas and Barry, 2005) which suggests  
543 that enamel will stay largely unaffected by antlerogenesis. In conclusion, none of our data  
544 suggests that antlerogenesis could be an important driver of body Ca isotope compositions  
545 and result in significant mismatch of Ca isotope compositions and trophic data.

#### 546 4.3 Nutrition control over bone and enamel $\delta^{44/42}\text{Ca}$ values in modern and fossil cervids

##### 547 4.3.1 Neonatal life history traits

548 We discussed how gestation, lactation and antlerogenesis could affect adult bone and  
549 enamel  $\delta^{44/42}\text{Ca}$  values, and neither of these phenomena can convincingly explain the low  
550  $\delta^{44/42}\text{Ca}$  values found in reindeer populations (Martin et al., 2017a). However, gestation and  
551 lactation not only affect adult Ca isotope composition, they also control juvenile Ca intakes  
552 and the Ca isotope composition of their tissues. For the 5 studied cervids with a preserved  
553 DP4 or unworn M1 (AB, JVB, JVI, ISO M1, ISO DP4), enamel mineralizing *in utero*  
554 systematically exhibits the lowest  $\delta^{44/42}\text{Ca}$  values recorded (figure 5, 6). DP4 teeth exhibit  
555 stable and low  $\delta^{44/42}\text{Ca}$  values relatively to third molars (M3) and adult bones, whereas M1  
556 teeth exhibit various rates of transition from early ontogenetic low  $\delta^{44/42}\text{Ca}$  values to late  
557 ontogenetic high  $\delta^{44/42}\text{Ca}$  values. A similar pattern of Ca isotope composition has been  
558 previously described in human deciduous teeth, in which a clear link between weaning  
559 practices and  $\delta^{44/42}\text{Ca}$  values has been described (Tacaíl et al., 2017). We thus propose that the  
560 transition from low  $\delta^{44/42}\text{Ca}$  values in DP4 and in the apex of M1, to high  $\delta^{44/42}\text{Ca}$  values in the  
561 neck of the M1, in the M2, M3 and adult bones is characteristic of the transition from  
562 maternal Ca transfer (during the gestation then the nursing) to post-weaning Ca intake (adult-

563 like diet). The mineralization timing and enamel  $\delta^{44/42}\text{Ca}$  values of red deer and reindeer are  
564 consistent with the 3-8 months of weaning age of these species (Miller, 1972; Mitchell et al.,  
565 1976; Brown and Chapman, 1991b; Jones et al., 2009). The specimens AB, JVB and ISO M1  
566 all reached adult Ca isotope composition at the neck of the M1. This suggests that they were  
567 weaned before four months considering the length of enamel mineralization (figure 5, 6 and  
568 appendix). Data from AJ (figure 6) also suggest a relatively early weaning, although the wear  
569 of the M1 limits the record of pre-weaning conditions. The JVB specimen constitutes an  
570 exception to this early transition of  $\delta^{44/42}\text{Ca}$  values in the M1. For this individual, the increase  
571 of  $\delta^{44/42}\text{Ca}$  values within the M1 seems flattened (see figure 5;  $\Delta_{\text{max-min}} = 0.17 \text{ ‰}$ ; intra-tooth 2  
572 s.d. = 0.12 ‰, n = 7), and enamel  $\delta^{44/42}\text{Ca}$  values only approach bone-like values within the  
573 M2 and M3 late mineralizing sections. This suggests a later weaning for this individual  
574 (around 8 months), or alternatively an earlier tooth mineralization. The fact that these weaning  
575 ages seem consistent with the observations of these species in the wild, supports that Ca  
576 isotopes are accurate for detecting *in utero*, milk feeding and weaning periods among  
577 mammals. These data also highlight that some individuals (like JVB) could display late  
578 dietary transition to purely adult diet (i.e. without milk), in a way that the transition is not yet  
579 complete when M2 teeth mineralize. This supports that milk consumption could have affected  
580 the previously published data of cervids from Jaurens (Martin et al., 2017a) and caused their  
581 suspiciously low enamel  $\delta^{44/42}\text{Ca}$  values. For these cervid species, we consequently advise to  
582 favor M3 enamel sampling to infer purely adult trophic information (when accessible). Note  
583 that in M3, enamel can then display higher  $\delta^{44/42}\text{Ca}$  values in case of an early breeding and  
584 subsequent lactation (see 4.2.2 section). When possible, we thus advise to analyze enamel  
585 zones which mineralized after weaning and prior to female sexual maturity. As the position of  
586 these zones are difficult to predict, especially for fossil species, we advise to use serial micro-

587 sampling in order to identify early post-weaning periods. This approach provides useful  
588 complementary information for ecological and physiological inferences and minimizes the  
589 potential of lactating females and nursing to affect trophic inferences based on  $\delta^{44/42}\text{Ca}$  data.

#### 590 4.3.2 *Osteophagia and mineral licks*

591 Osteophagia (i.e. bone consumption) and the consumption of natural mineral licks are  
592 two common sources of mineral supplementation that cervids, and more generally  
593 artiodactyls, use during periods of high mineral requirement (e.g. lactation, juvenile growth,  
594 antlerogenesis), notably to cope with phosphorus (P) or other element deficiency (Cowan and  
595 Brink, 1949; Kjos-Hanssen, 1973; Krausman and Bissonette, 1977; Marie, 1982; Grasman  
596 and Hellgren, 1993; Cáceres et al., 2011; Gambín et al., 2017). There is yet no direct measure  
597 of mineral supplementation effects on enamel Ca isotope composition in the literature.  
598 However, we can confidently assume that, because bones are generally  $^{44}\text{Ca}$ -depleted  
599 compared to plant products (Gussone and Heuser, 2016), antler or other bone consumption  
600 will result in lower dietary  $\delta^{44/42}\text{Ca}$  values (Gussone and Heuser, 2016; Martin et al., 2017a,  
601 2018). We can roughly estimate that this change of dietary  $\delta^{44/42}\text{Ca}$  value will be of 0 to -2‰,  
602 depending of the amount of consumed bones and their Ca isotope compositions (Heuser et al.,  
603 2011; Gussone and Heuser, 2016). Foraging on mineral licks would have the opposite effect  
604 on dietary  $\delta^{44/42}\text{Ca}$  value (about 0 to +1 ‰), because soils and rocks are generally  $^{44}\text{Ca}$ -  
605 enriched compared to plant products (Gussone and Heuser, 2016). These modifications of the  
606 dietary Ca isotope composition logically affect the  $\delta^{44/42}\text{Ca}$  values of growing enamel, with an  
607 intensity that will depend upon the rate of enamel growth and the duration of the mineral  
608 supplementation.

609 The resort to mineral supplementation by red deer from Bauges NRP has not been  
610 quantified. However, we know from a red deer population from Spain that about two hundred

611 individuals can consume about 966 g of antlers over 7 months, mainly during lactation,  
612 weaning and antlerogenesis periods (Estevez et al., 2008; Gambín et al., 2017). If we consider  
613 that antlers contained a maximum of 15% of Ca (see appendix), this would represent about  
614 0.7 g of Ca intake per individual. Considering that mineral supplementations were enhanced  
615 by the low P availability in the plants of the study site in Spain (Estévez et al., 2009; Gambín  
616 et al., 2017), we can expect a lower to similar intensity of mineral supplementations within  
617 the Bauges NRP red deer population. Such Ca intakes seem negligible over a year compared  
618 to plant and water sources, which suggests that mineral supplementations likely have a  
619 negligible influence on bone  $\delta^{44/42}\text{Ca}$  values. However, few individuals may have been  
620 responsible for most of this bone consumption (individuals were not identified in Gambín et  
621 al. (2017)), and cervids from this study likely had access to other bones and mineral sources  
622 than monitored antler stacks (Gambín et al., 2017). Therefore, it seems plausible to expect at  
623 least short excursions in enamel  $\delta^{44/42}\text{Ca}$  values (negative for osteophagia, positive for mineral  
624 licking) for individuals experiencing periods of important supplementation (i.e. lactation,  
625 weaning, antlerogenesis). Following this postulate, we suspect that the outlier  $\delta^{44/42}\text{Ca}$  value  
626 in the M3 of the JVB specimen has been influenced by osteophagia. This data point is  
627 characterized by an isolated low  $\delta^{44/42}\text{Ca}$  value, localized far after weaning in enamel formed  
628 around 15 months of age (figure 5), a period which could match the peak of supplementation  
629 reported in September by Gambín et al. (2017). Finally, we note that the two latest M2  
630  $\delta^{44/42}\text{Ca}$  values of AB (at 10 months) seem slightly higher than the average M2, M3 and bone  
631  $\delta^{44/42}\text{Ca}$  values of this specimen (figure 5). It is possible that this results from Ca intakes  
632 influenced by mineral licking, but the isotopic difference is tenuous, possibly artefactual, and  
633 does not match with the common periods of mineral supplementation recorded in Spain  
634 (Gambín et al., 2017).

635 Reindeer are also known to seasonally resort to mineral supplementation, likely to  
636 compensate for the low P, Ca and sodium content of the plants and lichens they consume  
637 (Grasman and Hellgren, 1993). Frequent antler chewing are reported in spring during the  
638 calving season (Kjos-Hanssen, 1973; Marie, 1982), as well as mineral licks, notably in the  
639 summer (Cowan and Brink, 1949). We have no data to quantify these supplementations, but it  
640 seems reasonable to suspect they can influence enamel  $\delta^{44/42}\text{Ca}$  values. A possible example is  
641 found within the M1 tooth of the JVJ specimen at 5 months (figure 6). This enamel zone  
642 constitutes the terminal part of the weaning transition, and is characterized by a higher  $\delta^{44/42}\text{Ca}$   
643 value than within the M2 of the specimen (or of any other enamel sample from Jaurens  
644 specimens). Because this critical period favors mineral supplementations in cervids (see  
645 previous paragraph), we suspect that this positive  $\delta^{44/42}\text{Ca}$  excursion is the result of mineral  
646 licking, although the very limited post-weaning JVJ dataset provides limited evidence for this.

647 If the effects of mineral supplementation on body Ca isotope composition are further  
648 confirmed, this proxy could be used to study this crucial survival behavior among modern and  
649 fossil mammals. As such, mineral supplementations however complicate the relation between  
650 trophic level and enamel Ca isotope composition. Thus, we emphasize the importance of  
651 considering mineral supplementation behaviors when using  $\delta^{44/42}\text{Ca}$  data for trophic  
652 interpretations. We notably suggest a specific attention toward this behavior for the study of  
653 artiodactyls from arid or tropical environments, because these environments are generally  
654 marked by a low P availability in plants, a trigger for mineral supplementations (Grasman and  
655 Hellgren, 1993).

#### 656 4.3.3 Plant Ca isotopic variability

657 Identifying and excluding enamel  $\delta^{44/42}\text{Ca}$  data affected by pre-weaning, lactation and  
658 short term mineral supplementation periods allow, with some limits (see previous section), to

659 identify Ca isotope data that are representative of trophic level. However, the important  
660 variability of plant Ca isotope compositions can also limit the trophic clustering of enamel  
661 and bone  $\delta^{44/42}\text{Ca}$  data, by generating isotopic variability among herbivores (Martin et al.,  
662 2018). Plant Ca isotope compositions combine a variability between plant organs and between  
663 plant taxa (Holmden and Bélanger, 2010; Gussone and Heuser, 2016; Schmitt, 2016; Moynier  
664 and Fujii, 2017; Martin et al., 2018; Griffith et al., 2020). The mean offset of  $-0.31 \pm 0.14$  ‰  
665 observed between the leaves of dicotyledons and monocotyledons (e.g. grasses) is notably  
666 suspected to cause the documented difference of  $-0.18 \pm 0.10$  ‰ between the enamel of  
667 browser herbivores (i.e. with a leaf-dominated diet) and of grazer herbivores (i.e. with a grass-  
668 dominated diet) (Martin et al., 2018). Red deer is described as a mixed feeder, changing  
669 seasonally or regionally between more browser to more grazer diets (Hearney and Jennings,  
670 1983; Gebert and Verheyden-Tixier, 2001; Storms et al., 2008; Berlioz et al., 2019). In the  
671 Bauges NRP, the grass proportion in the red deer diet has been estimated to change between  
672 20 % and 40 % from summer to winter (Redjadj et al., 2014), and could be lower during late  
673 winter, spring and early summer according to the tendencies observed at the limits of  
674 monitored periods (Redjadj et al., 2014). Changing diet proportions from 40 % grass and 60  
675 % leaves to 10 % grass and 90 % leaves would change the diet  $\delta^{44/42}\text{Ca}$  value of about 0.09 ‰,  
676 a result which is relatively close to the post-weaning range of 0.11 ‰ observed in the enamel  
677 record of the AB specimen (the red deer specimen with the most extensive post-weaning  
678 enamel record, figure 5). Our isotopic data are thus compatible, at the first order, with the  
679 known diet variability of this cervid population, although this estimation of 0.09 ‰ is built  
680 upon coarse approximations (notably that consumed grass  $\delta^{44/42}\text{Ca}$  value was exactly  $-0.31$  ‰  
681 lower than non-grass food  $\delta^{44/42}\text{Ca}$  value) and need further investigations. A higher resolution  
682 regarding the post-weaning enamel record, and a better constrain of the Ca isotope

683 composition of food items available at Bauges NRP (especially evergreen trees which are an  
684 important food source for these red deer, Redjadj et al. (2014)) would provide  $\delta^{44/42}\text{Ca}$  data  
685 that will be more comparable with  $\delta^{13}\text{C}$  records, dental micro-wear and stomach content data  
686 collected so far for this red deer population (Redjadj et al., 2014; Merceron et al., 2021). Such  
687 further studies could notably help resolving some discrepancies between dental micro-wear  
688 and stomach content estimations (i.e. higher versus lower grass content in the diet, Merceron  
689 et al. (2021)), and provide independent complementary information regarding  $\delta^{13}\text{C}$  data (e.g.  
690 diet and ecological niche).

691 Reindeers are also mixed-feeders, but consume lichen during winter and have a  
692 generally more browser diet compared to red deer (Hofmann, 1989; Mathiesen et al., 2000),  
693 an observation which is notably consistent with the higher  $\delta^{44/42}\text{Ca}$  values of reindeers  
694 compared to red deers when both co-exist within the same fauna (Dodat et al., 2021). After  
695 weaning, the AJ specimen (the reindeer with the most extensive post-weaning enamel record)  
696 exhibits a  $\delta^{44/42}\text{Ca}$  range of 0.25 ‰ (figure 6). As for red deer, this isotopic variability is  
697 compatible, at the first order, with the consequences expected from changing proportions of  
698 grass and other plant items in the diet. Within this browser to grazer-like diet continuum, the  
699 lowest enamel  $\delta^{44/42}\text{Ca}$  values would correspond to more grazer-like diet periods, whereas  
700 periods with the highest enamel  $\delta^{44/42}\text{Ca}$  values would correspond to more browser-like diet  
701 periods. A limit to this hypothesis is the potential occurrence of mineral supplementations  
702 which can modify the dietary Ca isotope composition independently of the plants (see section  
703 4.3.3). In this regard, combining  $\delta^{44/42}\text{Ca}$  data and  $\delta^{13}\text{C}$  data within a multi-proxy approach  
704 (e.g. Martin et al., 2018) would be a solid option to further investigate diet and mineral  
705 supplementation seasonality among these cervids.

## 706 4.3.4 Trophic position of Pleistocene fossil cervids

707 The previous discussion sections detail how to identify tooth and enamel parts that  
708 should be favored for trophic inter-specific comparisons (by identifying pre- and post-  
709 weaning periods, by detecting sections potentially disrupted by short term mineral  
710 supplementation, and by providing insight about intra-tooth  $\delta^{44/42}\text{Ca}$  variability). We applied  
711 this technic to three subadult to adult reindeers (AJ, JVJ, ISO M1) from the Late Pleistocene  
712 locality of Jaurens. The most suited enamel data points for trophic inter-specific comparisons  
713 are indicated in figure 6. Unfortunately, we do not have access to an extensive M2 and M3  
714 dataset for JVJ and ISO M1 specimens (figure 6). Therefore, we lake insight to determine if  
715 the enamel data points we selected for trophic inter-specific comparisons are entirely posterior  
716 to the weaning transition. Nevertheless, the selected data points of these specimens  
717 consistently range within the enamel Ca isotope compositions of AJ, which supports that they  
718 are representative of a post-weaning diet. Altogether, the weighted average (per specimen) of  
719 selected enamel  $\delta^{44/42}\text{Ca}$  values is +0.18 ‰ higher than previously published measures (Martin  
720 et al., 2017a). They consequently plot within the range of woolly rhinoceroses (*Coelodonta*  
721 *antiquitatis*, n = 3) (Wilcoxon rank-sum test, p-value = 0.1) and steppe bisons (*Bison priscus*,  
722 n = 3; Wilcoxon rank-sum test, p-value = 0.2) published by Martin et al. (2017a). This  
723 demonstrates that dismissing the data obtained from enamel affected by short term mineral  
724 supplementation or milk consumption, based on a serial micro-sampling approach, efficiently  
725 resolve the anomaly of  $^{44}\text{Ca}$  depletion previously reported in the enamel of reindeers from  
726 Jaurens. Serial micro-sampling is time and resource consuming and thus can hardly be used at  
727 the scale of a whole faunal assemblage, but this study proves that this technique is particularly  
728 suited to discuss of diet and behavior at the individual scale, or when some  $\delta^{44/42}\text{Ca}$  data are at  
729 odds with independently inferred trophic positions or diet.



730 **5. Conclusions**

731 In this paper we discussed the behavioral and physiological events likely to affect  
732 mammalian enamel and bone Ca isotope compositions, with two species of cervids as models  
733 (*Cervus elaphus*, *Rangifer tarandus*). Our results highlight that lactation is an effective  
734 source of Ca isotope variability as this phenomenon produced  $^{44}\text{Ca}$ -enriched isotope  
735 composition in bones of lactating females. Our study, however, failed to show any  
736 comparable gestation effect, likely because of long Ca residence time in cervid bones, and  
737 lower Ca fluxes or Ca isotope fractionation coefficients involved in cervid gestation.  
738 Similarly, antlerogenesis did not prove to be a significant driver of body Ca isotope  
739 composition in red deer. However, our data highlight that antlers display a different Ca  
740 isotopic signature than the rest of the skeleton, encouraging further studies. The Ca  
741 transferred from the cervid mother to the foetus during gestation has a similar isotope  
742 composition than milk according to data from enamel mineralizing *in utero*, at least close  
743 before birth. The transition from pre-parturition and pre-weaning Ca intakes to adult diet is  
744 clearly observed within the enamel of most of the studied individuals. Calcium isotopes can  
745 then be efficiently used for assessing weaning ages, providing the fact that no osteophagia is  
746 involved early in life, as this phenomenon is also able to generate low bone and enamel  
747  $\delta^{44/42}\text{Ca}$  values (at the opposite of what is expected from mineral licks foraging). Finally, this  
748 study demonstrates that serial micro-sampling of enamel is an appropriate method to  
749 disentangle part of ecological, physiological and environmental Ca isotope signals. This  
750 method allowed to accurately extract trophic information from the enamel  $\delta^{44/42}\text{Ca}$  values of  
751 the reindeers from the Pleistocene deposit of Jaurens. When possible, we thus encourage the  
752 use of this method in order to accurately retrieve diet and trophic signals from enamel  $\delta^{44/42}\text{Ca}$   
753 data. Such an approach would greatly benefit to paleoecology fields, as it makes Ca isotope

754 data more readily comparable with other diet proxy such as carbon and nitrogen isotopes.  
755 Further studies are needed to investigate other cases of discrepancy between  $\delta^{44/42}\text{Ca}$  data and  
756 trophic level, as well as to assess the variability of lactation, gestation and mineral  
757 supplementation signals among mammals. However, these results open great perspectives for  
758 the study of mammal physiology in addition to clarify the trophic inferences achievable with  
759 Ca isotopes.

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1062 **Table 1. Body mass data of red deer from Bauges NRP**

sex	age	mean	sd	n	lower	upper
F	A	98.05	12.82	447	81.58	114.52
F	J	52.00	8.75	223	40.73	63.27

F	SA	77.21	9.30	102	65.15	89.27
M	A	150.71	27.90	457	114.87	186.56
M	J	56.40	8.70	218	45.20	67.60
M	SA	96.05	13.66	187	78.44	113.66

1063

1064 NOTE. This table shows the total body mass data [kg] recorded on 1634 specimens of red  
1065 deer from Bauges NRP. Age classes referred as adult (A), subadult (SA) and juvenile (J).

1066

1067 **Figures and captions**1068 *Figure 1. Mass dependency*

1069 Three isotope plot:  $\delta^{43/42}\text{Ca}$  as a function of  $\delta^{44/42}\text{Ca}$  (‰, expressed relatively to ICP Ca Lyon)  
1070 for all samples and standards analyzed for Ca isotope compositions in this study. The  
1071 regression line of these Ca isotope compositions (central blue line) has a y-axis intercept of  
1072  $0.006 \pm 0.015$  (‰, 2 s.e.), indistinguishable from theoretical 0 ‰ intercept. The slope value of  
1073 this line is  $0.509 \pm 0.016$  (2 s.e.), indistinguishable from the 0.507 slope predicted by the  
1074 exponential mass-dependent fractionation law (black dotted line). Error bars at the bottom  
1075 right are average 2 s.d. for  $\delta^{43/42}\text{Ca}$  and  $\delta^{44/42}\text{Ca}$ . The two most external lines (blue) delimit the  
1076 prediction interval whereas the two lines (red) around the central line correspond to the 95 %  
1077 confidence interval of the regression line.

1078 *Figure 2. Sex and body mass control over bone  $\delta^{44/42}\text{Ca}$  values*

1079 Bone  $\delta^{44/42}\text{Ca}$  values of adult red deer specimens ( $\geq$  three years old) from Bauges NRP plotted  
1080 in function of their total body mass. The average double standard error of these measures  
1081 (Mean 2SE in the graph) is represented at the bottom right of the graph. The two vertical



1082 dotted lines mark the limits of body mass (65 and 105 kg) expected from females which  
1083 supposedly gave birth and lactate during the last birth season preceding their death. Red deer  
1084 silhouettes are modified from pictures of the public domain accessible in the following  
1085 website: [www.phylopic.org](http://www.phylopic.org).

1086 *Figure 3. Sex and age control over bone  $\delta^{44/42}\text{Ca}$  values*

1087 Bone  $\delta^{44/42}\text{Ca}$  values of red deer from Bauges NRP grouped by sex and age categories. Adult  
1088 red deer ( $\geq$  three years old) are represented by dots and sub-adults (two years old) by  
1089 triangles. Boxplots are plotted from adult male and lactating female data. The degree of  
1090 significance of the difference between these two groups is represented with stars (\*), with two  
1091 stars indicating a Wilcoxon rank-sum test: p-value  $< 0.01$ . The average double standard error  
1092 of these measures (Mean 2SE in the graph) is represented at the bottom right of the graph.  
1093 Red deer silhouettes are modified from pictures of the public domain accessible in the  
1094 following website: [www.phylopic.org](http://www.phylopic.org).

1095 *Figure 4. Antler Ca isotopic composition*

1096 Intra-individual variability of mandible and antler bone  $\delta^{44/42}\text{Ca}$  values from the SPB  
1097 specimen. In this graph antler micro-samples are plotted in function of their original position  
1098 from the sampled antler displayed in photo. Blue error bars represent the 2 s.e. intervals of  
1099 each sample. The horizontal black and red lines represent respectively the mean mandible  
1100 bone  $\delta^{44/42}\text{Ca}$  value of the specimen and the limits of its confidence interval ( $\pm 2$  s.e).

1101 *Figure 5. Enamel and bone  $\delta^{44/42}\text{Ca}$  variability of modern red deer*

1102 The  $\delta^{44/42}\text{Ca}$  values from bone and enamel micro-samples of AB and JVB specimens (modern  
1103 red deer, Bauges NRP). The horizontal black and red lines represent respectively the mean  
1104 bone  $\delta^{44/42}\text{Ca}$  value of each specimen and the limits of their confidence interval ( $\pm 2$  s.e).

1105 Micro-samples from DP4, M1, M2 and M3 teeth are respectively represented by purple  
1106 diamonds, red points, blue squares and green triangles. Dashed orange and cyan ellipses  
1107 respectively emphasize periods during which mineral licking and osteophagia events are  
1108 suspected. Error bars represent the 2 s.e. intervals for each sample. The age model used for  
1109 temporally anchor enamel micro-samples is described in section 2.4 and is extrapolated from  
1110 Brown and Chapman (1991a), with the only exception of enamel mineralizing *in utero* for  
1111 which ages are arbitrary. Teeth mineralization timings which served this model are displayed  
1112 at the bottom of the graph. Note that despite our micro-sampling procedure time averaging  
1113 likely affects each of these enamel micro-samples (see appendix). Red deer silhouettes are  
1114 modified from pictures of the public domain accessible in the following website:  
1115 [www.phylopic.org](http://www.phylopic.org).

1116 *Figure 6. Enamel  $\delta^{44/42}\text{Ca}$  variability of fossil reindeer*

1117 The  $\delta^{44/42}\text{Ca}$  values from bone and enamel micro-samples of AJ, JVJ, ISO M1 and ISO DP4  
1118 specimens (fossil reindeer). Note that ISO M1 and ISO DP4 are two distinct specimens that  
1119 have been merged in one graph only for visual convenience. Micro-samples from DP4, M1,  
1120 M2, M3 and P4 teeth are respectively represented by purple diamonds, red points, blue  
1121 squares, green triangles and inverted yellow triangles. The dashed orange ellipse emphasizes a  
1122 period during which mineral licking events are suspected. Dotted boxes contain points  
1123 identified as providing accurate trophic information (see section 4.3). Error bars represent  
1124 the 2 s.e. intervals of each sample. The age model used for temporally anchor enamel micro-  
1125 samples is described in section 2.4 and is extrapolated from Brown and Chapman, 1991a,  
1126 with the only exception of enamel mineralizing *in utero* for which ages are arbitrary. Teeth  
1127 mineralization timings which served this model are displayed at the bottom of the graph. Note  
1128 that despite our micro-sampling procedure time averaging likely affects each of these enamel

1129 micro-samples (see appendix). Reindeer silhouettes are pictures from the public domain  
1130 accessible in the following website: [www.phylopic.org](http://www.phylopic.org).

## 1131 **Appendix**

### 1132 *Bone and enamel mineralization patterns*

1133 This appendix further describes the nature and length of mineralization we consider for bones  
1134 and teeth. This text include the following references: (Ewbank et al., 1964; Biewener, 1990;  
1135 Brown and Chapman, 1991a, 1991b; Smith, 1998; Fricke et al., 1998; Passey and Cerling,  
1136 2002; Kohn, 2004; Hadjidakis and Androulakis, 2006; Pasteris et al., 2008; Stevens et al.,  
1137 2011; Blaine et al., 2015; Tacail, 2017; Trayler and Kohn, 2017; Green et al., 2017; Smith et  
1138 al., 2018).

### 1139 *Figure S1. Bone box model*

1140 This box model describes the evolution of a conceptual bone reservoir representing  $1.2 \times 10^6$   
1141 mg of Ca (in red) exchanging with an infinite reservoir (in purple) through  $500 \text{ mg} \cdot \text{d}^{-1}$  of input  
1142 and output Ca fluxes. Bone starts with a  $\delta^{44/42}\text{Ca}$  value of  $-0.5 \text{ ‰}$  and the infinite box is set to  
1143  $0 \text{ ‰}$ . Time is given in days. These reservoir sizes are inspired from the human model  
1144 described in Tacail (2017).

### 1145 *Table S1. Calcium isotope composition and supplementary information of red deer*

1146 This table includes all Ca isotope composition data collected on red deer in this study as well  
1147 as additional specimen and sample details (e.g. sample ID, sampling method, body mass).  
1148 When both data were available, total body mass was in average 1.28 bigger for males and  
1149 1.42 bigger for females than their respective gutted body mass. We applied this factor to  
1150 calculate the total body mass when only gutted body mass data were available. Total body  
1151 mass format is in bold when weighted post mortem (i.e. not converted from gutted body

1152 mass). Age format is in bold when directly recorded, other age values are inferred from tooth  
1153 eruption and attrition stages (Brown and Chapman, 1991a, 1991b).

1154 *Table S2. Calcium isotope composition and supplementary information of reindeer*

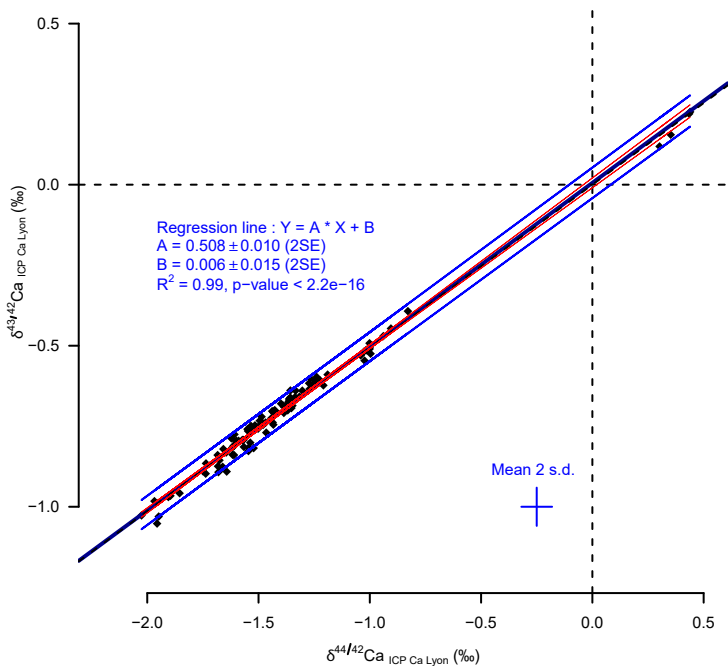
1155 This table includes all Ca isotope composition data collected on reindeer in this study as well  
1156 as additional specimen and sample details (e.g. sample ID, sampling method).

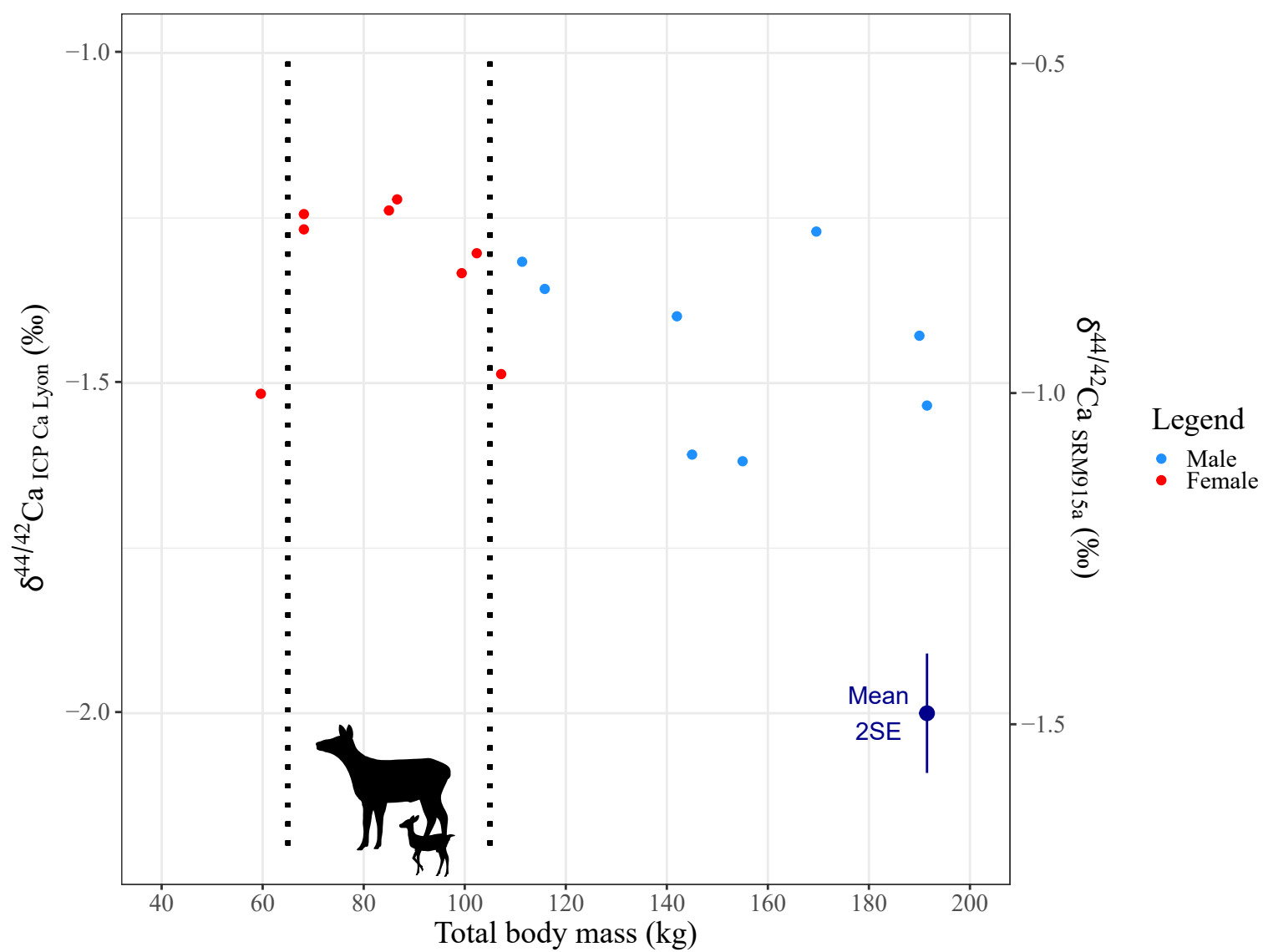
1157 *Table S3. Calcium isotope composition of reference materials*

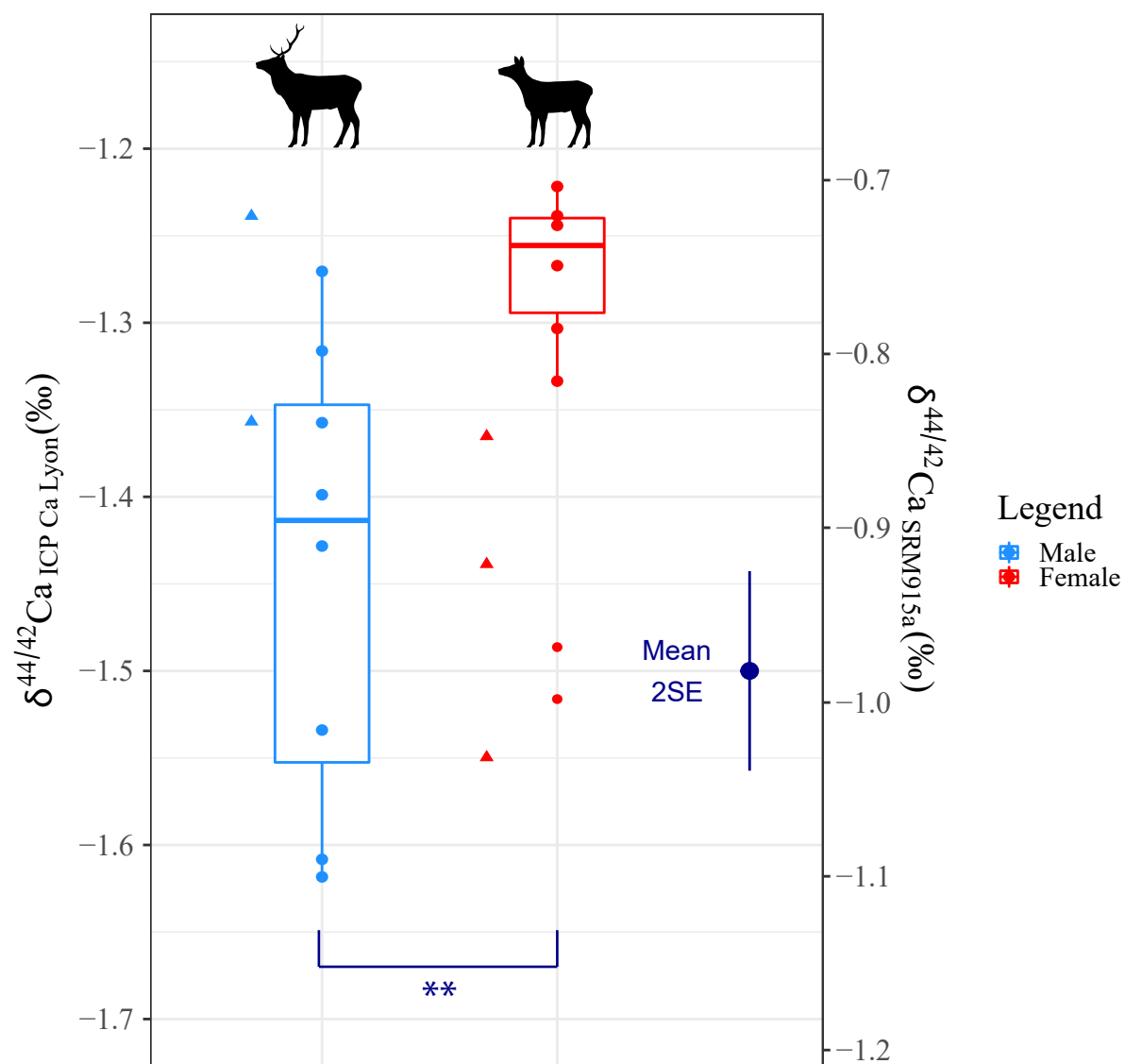
1158 This table includes all Ca isotope composition data collected in this study on SRM 1486  
1159 (NIST) and IAPSO (OSIL). Data of the same reference materials from previous studies are  
1160 summarized for comparison.

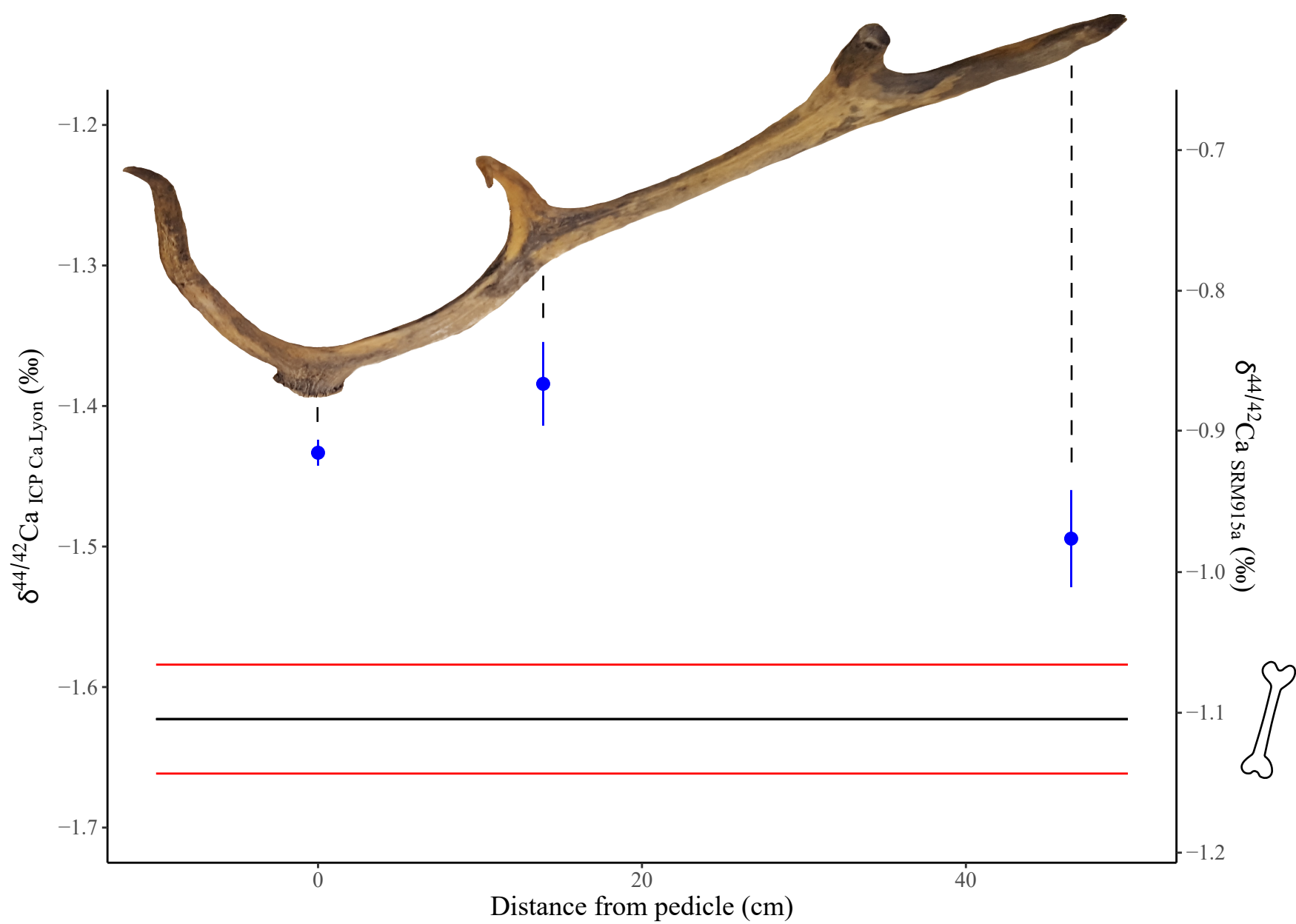
1161 *Table S4. Sample elemental composition*

1162 Sample elemental composition of 26 major and trace elements of herbaceous remains,  
1163 mandibles and antlers.

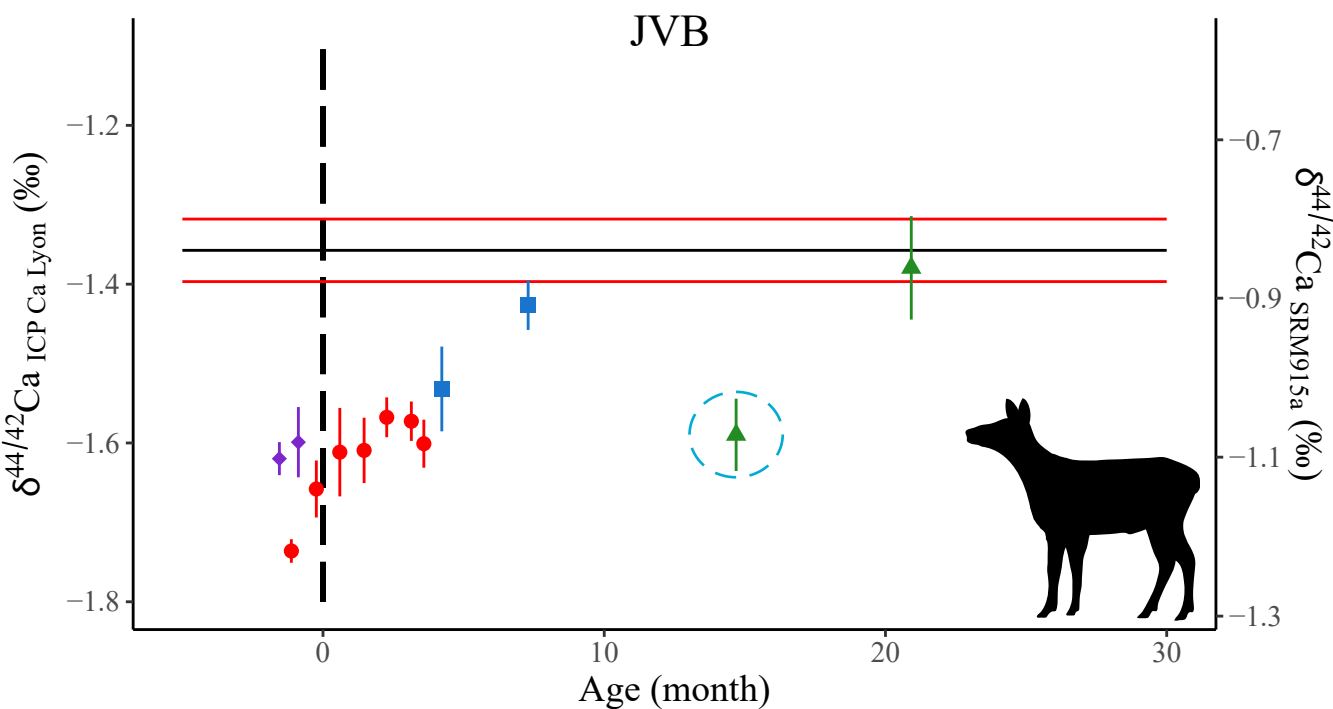
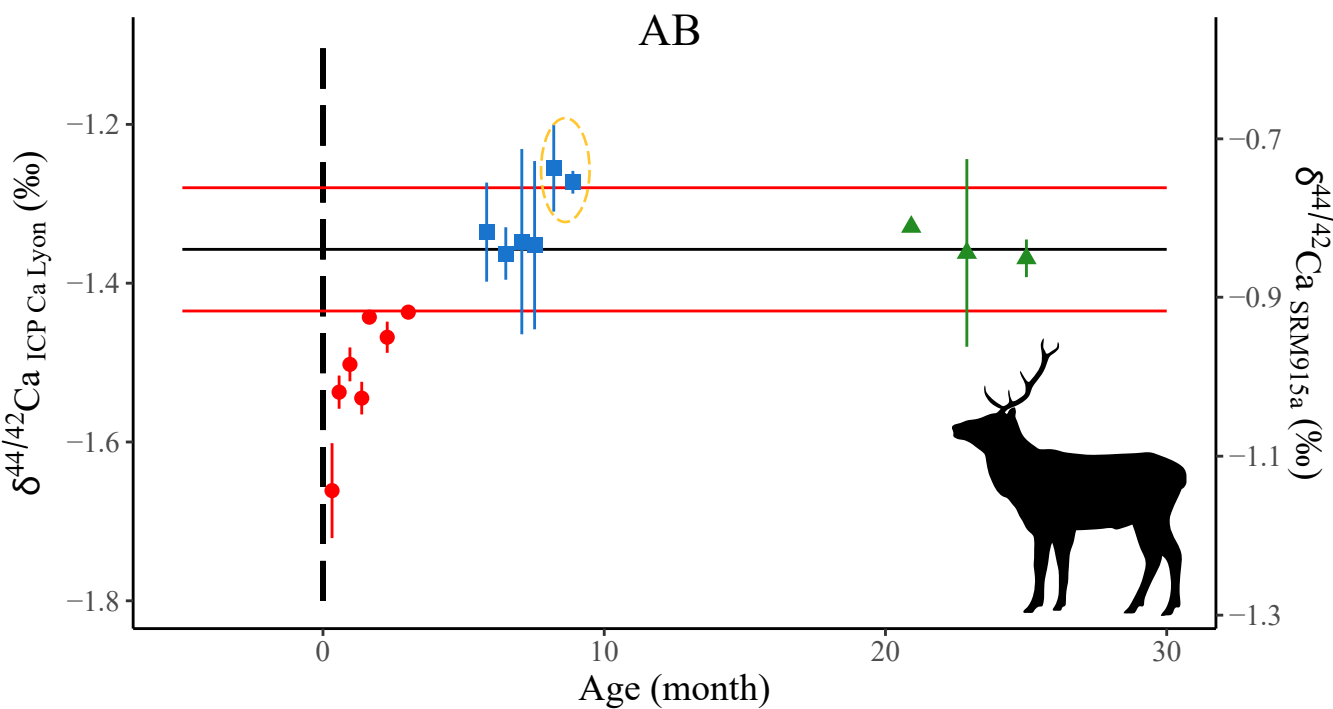


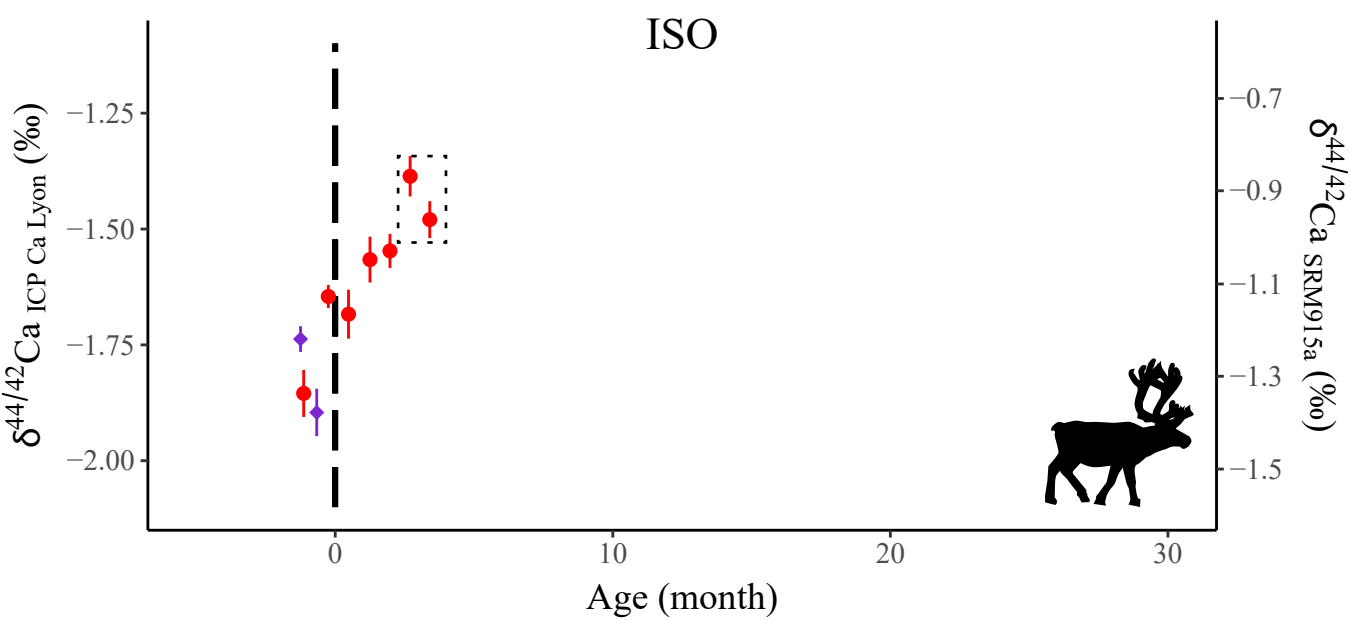
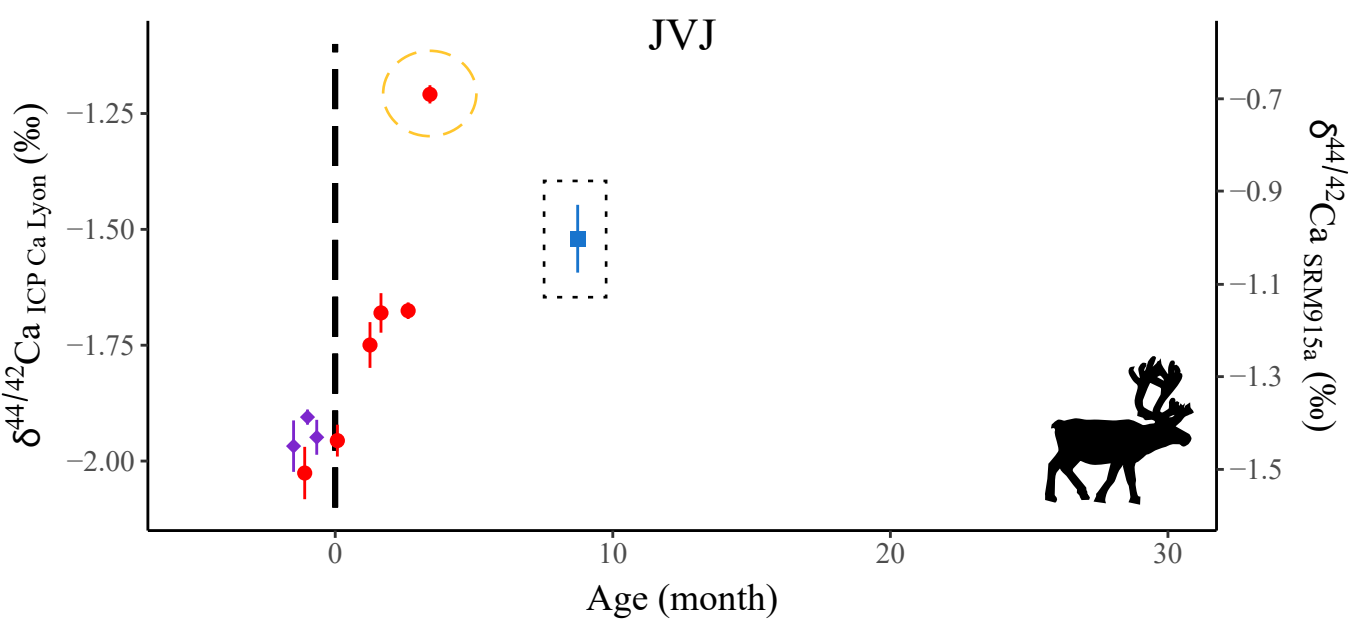
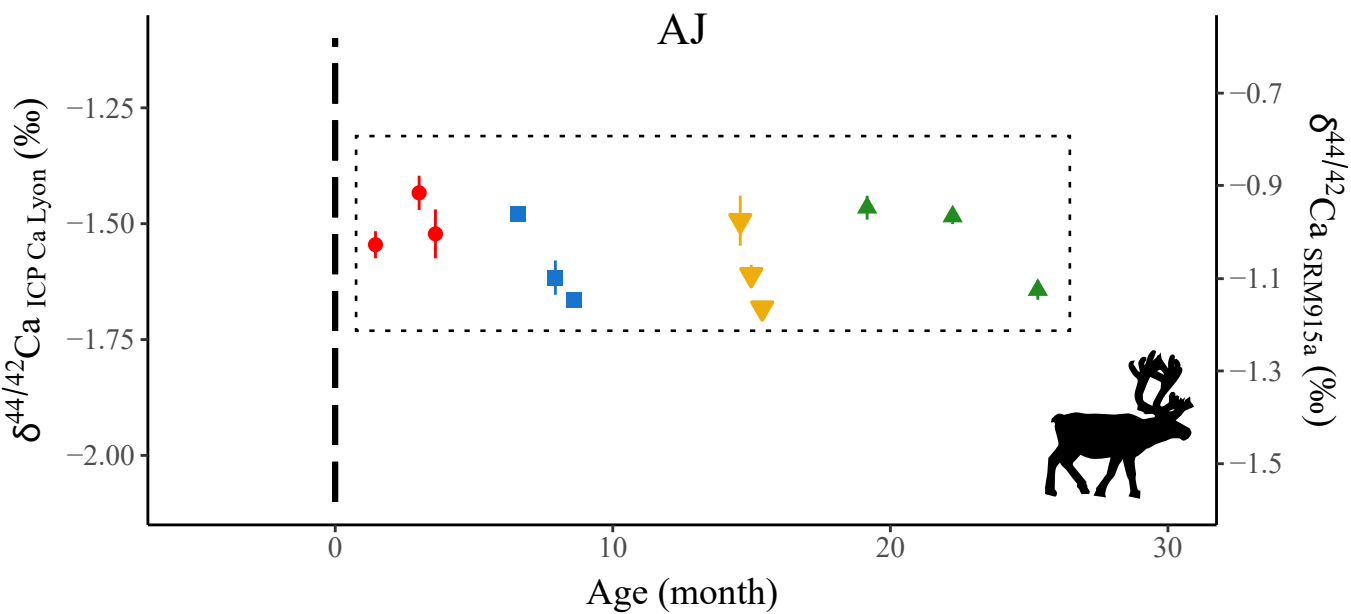


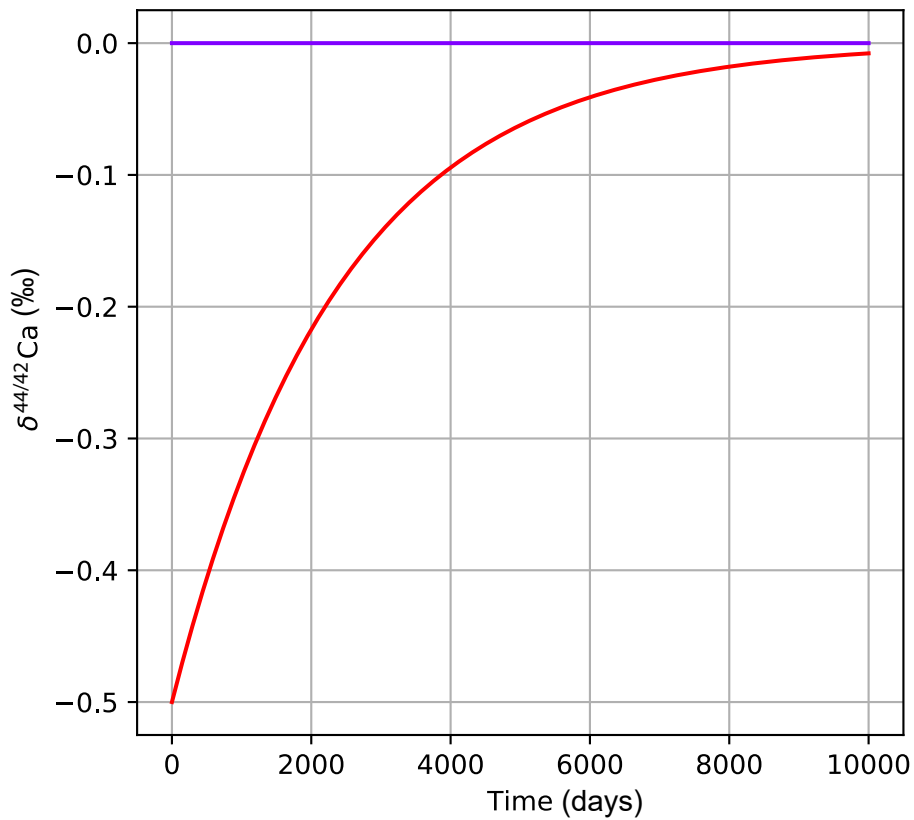












sex	age	mean	sd	n	lower	upper
F	A	98.05	12.82	447	81.58	114.52
F	J	52.00	8.75	223	40.73	63.27
F	SA	77.21	9.30	102	65.15	89.27
M	A	150.71	27.90	457	114.87	186.56
M	J	56.40	8.70	218	45.20	67.60
M	SA	96.05	13.66	187	78.44	113.66

Collection id	Lab name	Origin	Genus	Species	Tissue
UP-15CE0104	15CE0104 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE0106	15CE0106 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE0140	15CE0140 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE2616	15CE2616 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE2620	15CE2620 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE2655	15CE2655 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE3523	15CE3523 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE4526	15CE4526 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE4821	15CE4821 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE4823	15CE4823 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE4825	15CE4825 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE4929	15CE4929 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE4951	15CE4951 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE5028	15CE5028 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE5519	15CE5519 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE5616	15CE5616 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE5795	15CE5795 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE5837	15CE5837 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE7104	15CE7104 os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone
UP-15CE5672	AB M1-3	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M1-4	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M1-5	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M1-11	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M1-12	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M1-13	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M1-7	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M2-1	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M2-2	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M2-3	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M2-4	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M2-5	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M2-6	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M3-1	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M3-2	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB M3-3	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE5672	AB os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibule bone
UP-15CE3734	JVB DP4-1	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE3734	JVB DP4-2	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE3734	JVB M1-1	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE3734	JVB M1-2	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE3734	JVB M1-3	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE3734	JVB M1-4	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE3734	JVB M1-5	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE3734	JVB M1-6	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE3734	JVB M1-7	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE3734	JVB M2-1	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE3734	JVB M2-2	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE3734	JVB M3-1	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel

UP-15CE3734	JVB M3-2	Bauges	<i>Cervus</i>	<i>elaphus</i>	enamel
UP-15CE3734	JVB os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibule bone
MHNL-50002207	SPB B1	Europe	<i>Cervus</i>	<i>elaphus</i>	antler bone
MHNL-50002207	SPB B2	Europe	<i>Cervus</i>	<i>elaphus</i>	antler bone
MHNL-50002207	SPB B3	Europe	<i>Cervus</i>	<i>elaphus</i>	antler bone
MHNL-50002207	SPB os	Europe	<i>Cervus</i>	<i>elaphus</i>	mandibule bone

Sampling technique	Age [year]	Sex	ath.date [m/c]	Gutted.weight [kg]
handed drill	≥3	female	10/31/2015	61
handed drill	≥3	male	10/18/2015	87
handed drill	≥3	male	12/06/2015	142
handed drill	≥3	male	10/26/2015	na
handed drill	≥3	male	11/22/2015	149.5
handed drill	≥3	male	10/24/2015	na
handed drill	2	female	10/25/2015	na
handed drill	≥3	female	11/08/2015	72.1
handed drill	≥3	female	10/22/2015	42
handed drill	≥3	female	11/15/2015	70
handed drill	≥3	female	10/22/2015	48
handed drill	≥3	female	10/22/2015	48
handed drill	≥3	female	11/22/2015	75.5
handed drill	2	female	11/01/2015	na
handed drill	2	male	10/01/2015	70
handed drill	≥3	male	11/12/2015	132.5
handed drill	2	male	10/27/2015	na
handed drill	≥3	male	11/15/2015	122.5
handed drill	≥3	female	10/31/2015	na
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
edge-drilling procedure	≥3	male	12/20/2015	90.5
handed drill	≥3	male	12/20/2015	90.5
outer-drilling procedure	2	female	10/17/2015	70
outer-drilling procedure	2	female	10/17/2015	70
edge-drilling procedure	2	female	10/17/2015	70
edge-drilling procedure	2	female	10/17/2015	70
edge-drilling procedure	2	female	10/17/2015	70
edge-drilling procedure	2	female	10/17/2015	70
edge-drilling procedure	2	female	10/17/2015	70
edge-drilling procedure	2	female	10/17/2015	70
edge-drilling procedure	2	female	10/17/2015	70
edge-drilling procedure	2	female	10/17/2015	70
outer-drilling procedure	2	female	10/17/2015	70
outer-drilling procedure	2	female	10/17/2015	70
outer-drilling procedure	2	female	10/17/2015	70

outer-drilling procedure	2	female	10/17/2015	70
handed drill	2	female	10/17/2015	70
handed drill	≥3	male	na	na
handed drill	≥3	male	na	na
handed drill	≥3	male	na	na
handed drill	≥3	male	na	na



total.body.mass [kg]	n	rel to ICP Ca Lyon			
		Mean $\delta^{44/42}\text{Ca}$	Mean $\delta^{43/42}\text{Ca}$	Mean $\delta^{44/43}\text{Ca}$	2 s.d. $\delta^{44/42}\text{Ca}$
86.62 2		-1.22	-0.61	-0.61	0.04
111.36 2		-1.32	-0.66	-0.67	0.03
<b>190</b> 4		-1.43	-0.70	-0.72	0.07
<b>142</b> 2		-1.40	-0.68	-0.72	0.11
<b>191.5</b> 2		-1.53	-0.75	-0.78	0.10
<b>145</b> 2		-1.61	-0.78	-0.83	0.01
<b>61</b> 2		-1.44	-0.70	-0.73	0.08
102.382 2		-1.30	-0.64	-0.66	0.15
59.64 2		-1.52	-0.75	-0.77	0.01
99.4 3		-1.33	-0.64	-0.70	0.07
68.16 2		-1.24	-0.61	-0.64	0.01
68.16 2		-1.27	-0.60	-0.68	0.01
107.21 2		-1.49	-0.72	-0.78	0.04
<b>72.5</b> 2		-1.55	-0.76	-0.79	0.18
89.6 2		-1.36	-0.64	-0.70	0.06
169.6 2		-1.27	-0.63	-0.64	0.04
<b>76</b> 2		-1.24	-0.60	-0.63	0.01
<b>155</b> 3		-1.62	-0.82	-0.80	0.19
<b>85</b> 2		-1.24	-0.60	-0.63	0.39
115.84 2		-1.44	-0.74	-0.69	0.01
115.84 3		-1.47	-0.74	-0.72	0.03
115.84 2		-1.44	-0.73	-0.72	0.01
115.84 4		-1.54	-0.82	-0.73	0.04
115.84 3		-1.50	-0.76	-0.75	0.04
115.84 4		-1.54	-0.80	-0.75	0.04
115.84 2		-1.66	-0.88	-0.78	0.08
115.84 2		-1.27	-0.62	-0.65	0.02
115.84 2		-1.26	-0.62	-0.64	0.08
115.84 2		-1.35	-0.69	-0.66	0.15
115.84 2		-1.35	-0.69	-0.67	0.16
115.84 2		-1.36	-0.67	-0.69	0.05
115.84 2		-1.34	-0.66	-0.69	0.09
115.84 2		-1.37	-0.70	-0.67	0.03
115.84 2		-1.36	-0.67	-0.68	0.17
115.84 2		-1.33	-0.67	-0.67	0.00
115.84 5		-1.36	-0.66	-0.70	0.17
99.4 3		-1.60	-0.80	-0.81	0.08
99.4 3		-1.62	-0.79	-0.83	0.04
99.4 3		-1.60	-0.80	-0.79	0.05
99.4 3		-1.57	-0.79	-0.78	0.04
99.4 3		-1.57	-0.79	-0.78	0.04
99.4 3		-1.61	-0.81	-0.81	0.07
99.4 3		-1.61	-0.81	-0.80	0.10
99.4 4		-1.66	-0.82	-0.83	0.07
99.4 4		-1.74	-0.87	-0.87	0.03
99.4 3		-1.43	-0.70	-0.72	0.05
99.4 5		-1.53	-0.76	-0.77	0.12
99.4 3		-1.38	-0.69	-0.69	0.11

	99.44	-1.59	-0.80	-0.79	0.09
	99.44	-1.37	-0.67	-0.68	0.08
na	4	-1.43	-0.71	-0.72	0.02
na	4	-1.38	-0.69	-0.68	0.06
na	3	-1.49	-0.73	-0.75	0.06
na	3	-1.62	-0.79	-0.82	0.04

2 s.d. $\delta^{43/42}\text{Ca}$	2 s.d. $\delta^{44/43}\text{Ca}$	rel to SRM915a Mean $\delta^{44/42}\text{Ca}$
0.08	0.01	-0.70
0.01	0.02	-0.80
0.05	0.05	-0.91
0.04	0.10	-0.88
0.03	0.14	-1.02
0.08	0.06	-1.09
0.10	0.00	-0.92
0.09	0.06	-0.79
0.01	0.01	-1.00
0.01	0.07	-0.82
0.05	0.02	-0.73
0.00	0.01	-0.75
0.06	0.02	-0.97
0.07	0.12	-1.03
0.03	0.00	-0.84
0.04	0.09	-0.75
0.01	0.01	-0.72
0.12	0.11	-1.10
0.22	0.16	-0.72
0.04	0.03	-0.92
0.08	0.03	-0.95
0.04	0.04	-0.92
0.07	0.05	-1.03
0.04	0.02	-0.98
0.06	0.07	-1.02
0.01	0.07	-1.14
0.06	0.01	-0.75
0.06	0.02	-0.74
0.08	0.06	-0.83
0.00	0.09	-0.83
0.01	0.03	-0.84
0.10	0.00	-0.82
0.10	0.07	-0.85
0.14	0.01	-0.84
0.03	0.00	-0.81
0.09	0.09	-0.84
0.04	0.03	-1.08
0.06	0.07	-1.10
0.06	0.08	-1.08
0.02	0.04	-1.05
0.05	0.01	-1.05
0.04	0.06	-1.09
0.04	0.05	-1.09
0.08	0.01	-1.14
0.03	0.02	-1.22
0.03	0.04	-0.91
0.09	0.05	-1.01
0.07	0.05	-0.86

0.07	0.02	-1.07
0.05	0.07	-0.85
0.02	0.04	-0.92
0.07	0.02	-0.87
0.04	0.06	-0.98
0.02	0.04	-1.10

Collection id	Lab name	Origin	Genus	Species	Tissue
UCBL-FSL 451.409	AJ M1-1	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.409	AJ M1-2	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.409	AJ M1-3	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.409	AJ M2-1	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.409	AJ M2-2	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.409	AJ M2-3	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.409	AJ M3-1	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.409	AJ M3-2	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.409	AJ M3-3	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.409	AJ os	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	mandibule bone
FSL 451.409	AJ P3-1	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.409	AJ P3-2	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.409	AJ P3-3	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.398	ISO DP4-1	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.398	ISO DP4-5	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.384	ISO M1-1	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.384	ISO M1-2	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.384	ISO M1-3	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.384	ISO M1-4	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.384	ISO M1-5	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.384	ISO M1-6	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.384	ISO M1-7	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.389	JVJ DP4-1	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.389	JVJ DP4-2	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.389	JVJ DP4-3	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.389	JVJ M1-1	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.389	JVJ M1-2	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.389	JVJ M1-3	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.389	JVJ M1-4	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.389	JVJ M1-5	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.389	JVJ M1-6	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.389	JVJ M2-1	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	enamel
FSL 451.389	JVJ os	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	mandibular bone

Sampling technique	n	rel to ICP Ca Lyon			
		Mean $\delta^{44/42}\text{Ca}$	Mean $\delta^{43/42}\text{Ca}$	Mean $\delta^{44/43}\text{Ca}$	2 s.d. $\delta^{44/42}\text{Ca}$
outer-drilling procedure	3	-1.52	-0.82	-0.71	0.09
outer-drilling procedure	3	-1.43	-0.75	-0.67	0.06
outer-drilling procedure	3	-1.55	-0.83	-0.71	0.05
outer-drilling procedure	3	-1.67	-0.88	-0.78	0.02
outer-drilling procedure	3	-1.62	-0.84	-0.78	0.06
outer-drilling procedure	3	-1.48	-0.74	-0.73	0.01
outer-drilling procedure	3	-1.64	-0.89	-0.76	0.04
outer-drilling procedure	3	-1.48	-0.74	-0.75	0.03
outer-drilling procedure	3	-1.47	-0.77	-0.71	0.04
outer-drilling procedure	5	-1.00	-0.49	-0.50	0.14
outer-drilling procedure	3	-1.68	-0.87	-0.80	0.01
outer-drilling procedure	3	-1.61	-0.84	-0.76	0.04
outer-drilling procedure	3	-1.49	-0.75	-0.75	0.09
edge-drilling procedure	2	-1.90	-0.97	-0.93	0.07
edge-drilling procedure	3	-1.74	-0.90	-0.84	0.05
edge-drilling procedure	4	-1.48	-0.75	-0.73	0.08
edge-drilling procedure	4	-1.39	-0.71	-0.68	0.09
edge-drilling procedure	2	-1.55	-0.76	-0.76	0.05
edge-drilling procedure	2	-1.57	-0.81	-0.77	0.07
edge-drilling procedure	3	-1.68	-0.84	-0.84	0.09
edge-drilling procedure	3	-1.65	-0.83	-0.81	0.04
edge-drilling procedure	3	-1.85	-0.96	-0.90	0.09
outer-drilling procedure	3	-1.95	-1.03	-0.92	0.07
outer-drilling procedure	3	-1.91	-0.97	-0.92	0.03
outer-drilling procedure	3	-1.97	-0.98	-0.99	0.10
outer-drilling procedure	3	-1.21	-0.62	-0.60	0.03
outer-drilling procedure	3	-1.68	-0.89	-0.80	0.07
outer-drilling procedure	3	-1.96	-1.05	-0.92	0.06
outer-drilling procedure	2	-1.68	-0.86	-0.82	0.03
outer-drilling procedure	2	-1.75	-0.89	-0.85	0.07
outer-drilling procedure	2	-2.03	-1.03	-0.99	0.08
outer-drilling procedure	4	-1.52	-0.76	-0.75	0.15
outer-drilling procedure	3	-0.94	-0.47	-0.48	0.17

		rel to SRM915a
2 s.d. $\delta^{43/42}\text{Ca}$	2 s.d. $\delta^{44/43}\text{Ca}$	Mean $\delta^{44/42}\text{Ca}$
0.01	0.08	-1.00
0.14	0.08	-0.92
0.13	0.15	-1.03
0.08	0.11	-1.15
0.10	0.02	-1.10
0.01	0.05	-0.96
0.08	0.06	-1.13
0.03	0.05	-0.97
0.04	0.04	-0.95
0.10	0.06	-0.48
0.04	0.08	-1.16
0.04	0.04	-1.09
0.15	0.07	-0.98
0.10	0.03	-1.38
0.04	0.04	-1.22
0.06	0.07	-0.96
0.12	0.04	-0.87
0.05	0.02	-1.03
0.02	0.09	-1.05
0.03	0.04	-1.17
0.07	0.04	-1.13
0.07	0.06	-1.34
0.05	0.04	-1.43
0.01	0.04	-1.39
0.12	0.02	-1.45
0.06	0.07	-0.69
0.12	0.07	-1.16
0.06	0.10	-1.44
0.03	0.02	-1.16
0.02	0.07	-1.23
0.10	0.01	-1.51
0.12	0.06	-1.00
0.09	0.08	-0.42

Standard name	Provider	Study
SRM1486	NIST	this study Martin et al. 2018 Tacail et al. 2017 Tacail et al. 2016 Heuser and Eisenhauer 2008
IAPSO	OSIL	this study Martin et al. 2015 Tacail et al. 2014 Compiled in Martin et al. 2015 from 16 studies

#### Standard conversions

All standards and datasets from the literature expressed in  $\delta^{44/40}\text{Ca}$  values were converted to  $\delta^{44/42}\text{Ca}$ . The constant difference of  $-0.518 \pm 0.025 \text{ ‰}$  between standards measured against SRM915a versus



n	$\delta^{44/42}\text{Ca}_{\text{ICP Ca Lyon}}$	2 s.d.
88	-1.00	0.07
101	-1.05	0.13
147	-1.03	0.12
120	-1.03	0.13
142	-1.02	0.12
14	0.38	0.06
5	0.41	0.12
2	0.41	0.06
-	0.41	0.07

Ca by dividing by 2.048, as calculated using the exponential mass dependent fractionation law (supple  
us ICP Ca Lyon (supplementaries from Martin et al. 2018) was used to calculate the corresponding iso

ementaries from Martin et al. 2018).

otope compositions of international standards from the literature with respect to ICP Ca Lyon.

Collection id	Lab name	Origin	Genus	Species	sample type	ca [%]
MNHL-50002207	SPB B1	Europe	<i>Cervus</i>	<i>elaphus</i>	antler bone	14.56
MNHL-50002207	SPB B2	Europe	<i>Cervus</i>	<i>elaphus</i>	antler bone	8.99
MNHL-50002207	SPB B3	Europe	<i>Cervus</i>	<i>elaphus</i>	antler bone	12.43
MNHL-50002207	SPB os	Europe	<i>Cervus</i>	<i>elaphus</i>	mandibular bone	22.99
FSL 451.409 os	AJ os	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	mandibular bone	27.87
FSL 451.389 os	JVJ os	Jaurens	<i>Rangifer</i>	<i>tarandus</i>	mandibular bone	27.32
UP-15CE3734	JVB os	Bauges	<i>Cervus</i>	<i>elaphus</i>	mandibular bone	21.29
AB F	AB F	Bauges			grass	1.83
JVB F	JVB F	Bauges			grass	0.99

\* : below detection limit

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p [%]	fe [ppm]	s [ppm]	al [ppm]	ba [ppm]	k [ppm]
7.83	*	6100.1	*	50.1	*
5.10	*	11481.3	*	61.0	2933.5
6.61	*	8465.3	*	39.6	1098.6
11.86	*	8969.5	*	87.7	176.8
13.49	5408.1	2250.0	1838.7	161.7	*
13.71	*	2306.2	1518.7	172.8	*
11.56	*	2181.3	*	98.7	387.0
0.54	313.1	1554.3	223.5	35.4	1298.1
0.50	279.6	2126.6	*	8.8	1419.5

mg [ppm]	mn [ppm]	na [ppm]	sr [ppm]	y [ppm]	la [ppm]
1953.0	13.5	3994.7	116.7	*	9.1
1800.2	11.8	11011.2	58.4	*	8.7
2978.1	2.5	7272.7	57.7	*	5.4
3876.6	13.2	7861.5	126.0	*	4.9
658.5	1696.6	3256.0	109.5	46.8	35.7
638.9	15.1	3150.4	119.5	14.3	18.6
6580.1	1.0	6996.0	110.8	*	5.7
1095.1	219.6	2965.4	23.2	*	1.4
826.5	30.7	4642.3	21.6	*	1.4

ce [ppm]	pr [ppm]	nd [ppm]	sm [ppm]	eu [ppm]	gd [ppm]	tb [ppm]
*	*	*	*	*	*	*
*	*	*	*	*	*	*
*	*	*	*	*	*	*
*	*	*	*	*	*	*
12.1	4.8	23.3	3.6	0.9	4.1	*
1.6	1.5	7.6	1.0	*	1.3	*
*	*	*	*	*	*	*
*	*	*	*	*	*	*
*	*	*	*	*	*	*

dy [ppm]	ho [ppm]	er [ppm]	tm [ppm]	yb [ppm]	lu [ppm]
*	*	*	*	*	*
*	*	*	*	*	*
*	*	*	*	*	*
*	*	*	*	*	*
3.0	0.8	2.3	*	2.0	*
*	*	*	*	*	*
*	*	*	*	*	*
*	*	*	*	*	*
*	*	*	*	*	*