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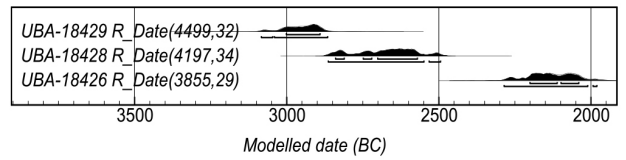
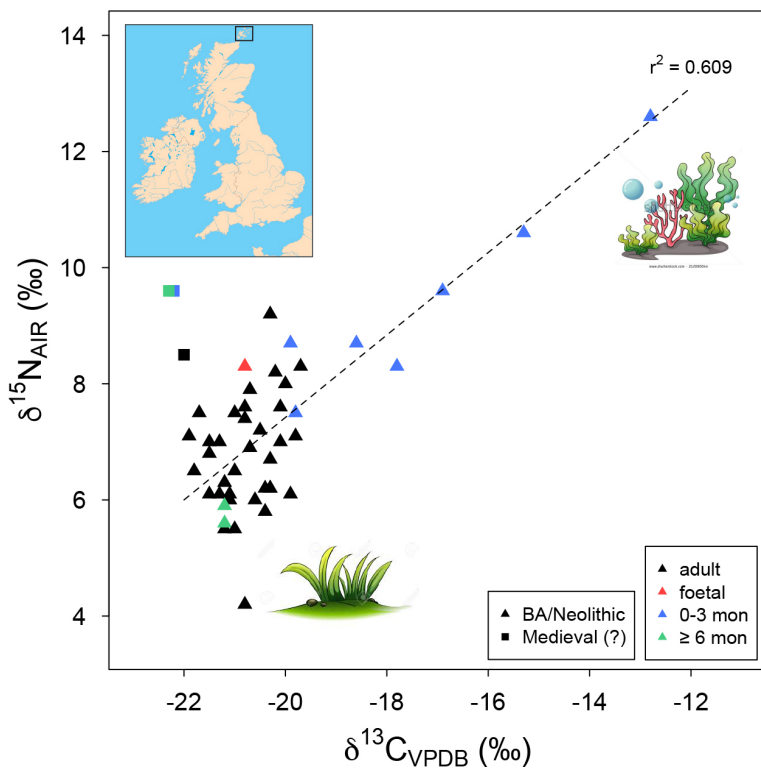
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# Further isotopic evidence for seaweed-eating sheep from Neolithic Orkney

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## Abstract

The antiquity of the practice of grazing on and/or foddering with seaweed is of interest in terms of understanding animal management practices in northwest Europe, where provision had to be made for overwintering. Orkney holds a special place in this discussion, since the sheep of North Ronaldsay have been confined to the seashores since the early nineteenth century, and are entirely adapted to a diet consisting mainly of seaweeds. Here, we report the results of stable carbon and nitrogen isotope analysis of twenty-five faunal specimens from the Neolithic chambered tomb of Quanterness, Orkney. Three of the 12 sheep analysed show elevated  $\delta^{13}\text{C}$  values that can only be explained by the consumption of seaweed. Radiocarbon dates place two of the three animals in the Neolithic, coeval with the use of the monument for burial, while the third animal dates to the Chalcolithic/Early Bronze Age. The findings are placed into the wider context of previous isotopic analyses of domestic fauna from prehistoric Orkney. A disjoint is noted between the results for bone collagen – where seaweed consumption seems to relate to the pre-natal period, since all the animals with high  $\delta^{13}\text{C}$  values are less than ca. three months of age – and previous studies using high-resolution sequential enamel measurements, which suggest a repeated pattern of winter consumption of seaweed in older animals.

**Key words:** stable carbon isotopes; Quanterness chambered tomb; palaeodietary modelling; marine reservoir effect

49 **1. Introduction**

50 The extension of the Neolithic way of life to the fringes of northwest Europe posed new  
51 challenges, taking domesticated plants and animals far from their original habitats in the  
52 Near East. For the latter, the short growing season of browse and graze meant that  
53 provision must have been made for the overwintering of domestic stock (Amorosi *et al.*  
54 1998). One resource available year-round along the coasts of northwest Europe is  
55 seaweed (e.g., *Palmaria palmata*, *Fucus* sp., *Laminaria* spp.). Historically, there is  
56 abundant evidence for the use of this resource, usually in dried form, as feed for both  
57 cattle and sheep (Chapman and Chapman 1980; Fenton 1978; Hallson 1964;  
58 Indergaard and Minsaas 1992; Kelly 1997; Makkar *et al.* 2016; Martin 1703). Without  
59 doubt the most dramatic evidence for this practice comes from North Ronaldsay in  
60 Orkney, where a sea-wall was built around the entire island's circumference in the early  
61 19<sup>th</sup> century to confine sheep to the seashore for most of the year (Fenton 1978;  
62 Hansen *et al.* 2003). Thus the question arises as to when this practice first emerged.  
63 The fact that consumption of seaweed leaves a distinct signal in the animals' stable  
64 carbon ( $\delta^{13}\text{C}$ ) and oxygen ( $\delta^{18}\text{O}$ ) isotope signatures – effectively making them appear  
65 isotopically similar to marine organisms (Ambers 1990) – provides the opportunity to  
66 explore this question with zooarchaeological remains. A small number of cases of  
67 sheep consuming seaweed in Orkney during the Neolithic have been previously  
68 identified using this method (Balasse *et al.* 2005; 2006; 2009; Balasse and Tresset  
69 2009; Schulting *et al.* 2004; Schulting and Richards 2009). Here, we provide new  
70 evidence from the results of a programme of stable carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ )  
71 isotope analysis and accelerator mass spectrometry (AMS) radiocarbon dating of a  
72 faunal assemblage from the Middle-Late Neolithic chambered tomb of Quanterness,  
73 Mainland, Orkney.

74

75 **2. Overview of stable carbon and nitrogen isotope analysis**

76 Measurements of bone collagen stable carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ ) values are  
77 frequently used in archaeology to investigate the major sources of dietary protein  
78 (Ambrose and Norr 1993; Lee-Thorp 2008). The values obtained via isotope ratio mass  
79 spectrometry (IRMS) provide a relatively long-term average of primarily protein intake,  
80 though the exact length of time represented will depend on the rate of remodeling of the

81 sampled bone, but will always be more rapid in young, growing animals. The ratios of  
82 stable C and N isotopes incorporated into animal tissues are driven by the isotopic  
83 composition of major dietary sources. Marine organisms, including seaweed, shellfish,  
84 fish and sea mammals, are enriched in  $^{13}\text{C}$  relative to  $^{12}\text{C}$  due to the fact that the ocean  
85 serves as a sink for the heavier isotope (Boutton 1991; Sharp 2007). As a result,  
86 organisms obtaining a significant proportion of their dietary protein from marine foods  
87 will exhibit higher  $\delta^{13}\text{C}$  values (ca.  $-12 \pm 1\text{‰}$ ) than those subsisting solely on  $\text{C}_3$   
88 terrestrial foods, which provide lower values (ca.  $-21 \pm 1\text{‰}$ ) for bone collagen (Richards  
89 and Hedges 1999). The consumption of  $\text{C}_4$  plants such as maize and millet would result  
90 in even higher bone collagen values than the consumption of marine foods, but as no  
91 such plants were found in northwest Europe during the study period, they need not be  
92 considered here.

93  
94 Stable nitrogen isotope ratios are used to investigate trophic levels. There is a variable  
95 but broadly predictable increase of ca. 3–5‰ between dietary item and consumer tissue  
96 for each step in the food chain (Ambrose 2000; Caut et al. 2009; Hedges and Reynard  
97 2007; Schoeninger and DeNiro 1984). This range is generally cited for human  
98 consumers, and may be towards its lower end for most herbivores. The comparable  
99 effect in  $\delta^{13}\text{C}$  is considerably smaller, about 1‰ (Bocherens and Drucker 2003; Lee-  
100 Thorp *et al.* 1989). The ocean is also enriched in  $^{15}\text{N}$  relative to atmospheric  $\text{N}_2$  (defined  
101 as 0‰), the latter serving as the ultimate source of nitrogen for terrestrial plants  
102 (Peterson and Fry 1987). Thus marine plants will generally have higher  $\delta^{15}\text{N}$  values  
103 than most temperate terrestrial plants under natural conditions (i.e., in the absence of  
104 anthropogenic input). Furthermore, because marine food webs are considerably more  
105 complex (i.e., involve more steps) than terrestrial mammalian food webs, there is scope  
106 for much greater trophic level enrichment, such that high-level marine carnivores can  
107 exhibit collagen  $\delta^{15}\text{N}$  values of +16‰ or more (Schoeninger and DeNiro 1984). Other  
108 factors can also result in  $^{15}\text{N}$  enrichment, most notably aridity, but this can safely be  
109 excluded from discussions pertaining to Orkney.

110

### 111 **3. Materials and Methods**

112 The Quanterness chambered tomb is located near the east-central coast of Mainland  
113 Orkney, northern Scotland (Figure 1). It serves as one of the two type-sites for the  
114 Quanterness-Quoyness type of passage tomb (also known as the Maes-Howe type).  
115 Excavated by Colin Renfrew in the 1970s (Renfrew 1979), the site yielded a large  
116 human skeletal assemblage (Crozier 2012), as well as ceramic, lithic and faunal  
117 remains. A recent dating programme focusing on the human remains placed the use of  
118 the monument for burial in the second half of the fourth millennium BC, continuing into  
119 the first quarter of the third millennium (Schulting *et al.* 2010). The original dating  
120 programme also identified one example (Pit C) of deposition of human remains in the  
121 third quarter of the third millennium BC (Renfrew 1979).

122  
123 For this study, twenty-five faunal bone samples from the Quanterness assemblage were  
124 selected for  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  analysis. The samples included domestic sheep (*Ovis aries*,  
125  $n=14$ , all left humeri; 1 foetal, 8 juveniles, 1 adolescent, 4 adults), domestic cattle (*Bos*  
126 *Taurus*,  $n=6$ , pelvae and ribs; 3 perinatal, 3 adults), domestic pig (*Sus scrofa*,  $n=3$ ,  
127 ulnae; 1 infant, 1 juvenile, 1 adult), dog (*Canis domesticus*,  $n=1$ , right femur; adult) and  
128 red deer (*Cervus elaphus*,  $n=1$ , left humerus; adolescent). The identification of the  
129 sampled humeri as sheep rather than goat is not based on their morphology (though  
130 this is possible – see Zeder and Lapham 2010), but rather on the scarcity of identified  
131 goat remains in Neolithic and Bronze Age Orkney overall. They will be referred to here  
132 as ‘sheep’; while there is a possibility that some are goat, this does not impact on the  
133 larger discussion.

134

135 Figure 1. Map of Orkney showing locations mentioned in the text.

136

137 The sheep/goats (henceforth ‘sheep’) were aged using standards in Moran and  
138 O’Connor (1994) and Popkin *et al.* (2012). One complete but very small humerus  
139 (greatest length = 35.2mm) is from a foetal lamb far from full term (McDonald *et al.*  
140 1977). Six animals are aged between birth and ca. 3 months based on the lengths of  
141 (66-70mm) for three complete humeri, and a comparison of maximum breadth of these  
142 specimens against the three incomplete elements. Three further humeri were in the  
143 process of fusing distally, placing them at  $\geq 6$  months. Finally, four animals are classed

144 as adults based primarily on their size, confirmed by the fully fused proximal humerus in  
145 the single complete specimen (>36 months).

146  
147 Collagen was extracted from the samples following a modified Longin procedure  
148 (Longin 1971; Richards and Hedges 1999). Measurements were made in duplicate on a  
149 SerCon 'Callisto' continuous flow IRMS coupled to an elemental analyser at the  
150 Research Laboratory for Archaeology and the History of Art, University of Oxford. An  
151 alanine standard was used to correct for machine drift and calculate the measurement  
152 precision ( $1\sigma$ ) at 0.2‰ for  $\delta^{13}\text{C}$  and  $\pm 0.3\%$  for  $\delta^{15}\text{N}$ .  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  are reported as per  
153 mil (‰) relative to the international standards VPDB and AIR, respectively. C:N values  
154 are reported as atomic ratios and serve as a check on collagen preservation (cf DeNiro  
155 1985).

156  
157 AMS radiocarbon dating was undertaken at the  $^{14}\text{C}$ CHRONO laboratory at Queen's  
158 University Belfast. The sample  $^{14}\text{C}/^{12}\text{C}$  ratio was background corrected and normalised  
159 to the HOXII standard (SRM 4990C; National Institute of Standards and Technology)  
160 and corrected for isotopic fractionation using the AMS-measured  $\delta^{13}\text{C}$  to account for  
161 both natural and machine fractionation. The  $^{14}\text{C}$  age and associated error were  
162 calculated using the Libby half-life (5568 years) following the conventions of Stuiver and  
163 Polach (1977). Nine samples were selected, targeting all the domestic species  
164 represented at Quanterness, as well as one of the small number of red deer elements.  
165 The main focus, however, was on sheep, since firstly, this taxon dominates the faunal  
166 assemblage (Clutton-Brock 1979), and secondly, the  $\delta^{13}\text{C}$  results highlighted  
167 considerable variability, and the sources of this variation were of particular interest. All  
168 calibrated dates are reported at 95.4% confidence.

169

### 170 3. Results

171 The faunal stable isotope results from Quanterness are provided in Table 1 and plotted  
172 in Figure 2. All samples passed collagen quality criteria including collagen yields and  
173 C:N ratios (Ambrose 1990; DeNiro 1985; van Klinken 1999).

174

<i>Cat. No.</i>	<i>Species, Latin name</i>	<i>Species</i>	<i>Element</i>	<i>Age</i>	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	<i>C:N</i>
3074.22	<i>Ovis aries</i>	sheep	L humerus	foetal	-20.8	8.3	3.3

2491.04	<i>Ovis aries</i>	sheep	L humerus	0-3 mon	-17.8	8.3	3.3
4084.48	<i>Ovis aries</i>	sheep	L humerus	0-3 mon	-19.8	7.5	3.3
146.07	<i>Ovis aries</i>	sheep	L humerus	0-3 mon	-18.6	8.7	3.3
4084.2	<i>Ovis aries</i>	sheep	L humerus	0-3 mon	-16.9	9.6	3.3
3072.03	<i>Ovis aries</i>	sheep	L humerus	0-3 mon	-19.9	8.7	3.2
4029.07	<i>Ovis aries</i>	sheep	L humerus	0-3 mon	-22.2	9.6	3.3
4081.80	<i>Ovis aries</i>	sheep	L humerus	ca. 6 mon	-22.3	9.6	3.2
2416.03	<i>Ovis aries</i>	sheep	L humerus	> 6 mon	-21.2	5.9	3.3
4570.02	<i>Ovis aries</i>	sheep	L humerus	> 6 mon	-21.2	5.6	3.3
1328.02	<i>Ovis aries</i>	sheep	L humerus	adult	-20.4	5.8	3.3
249.11	<i>Ovis aries</i>	sheep	L humerus	adult	-20.7	6.9	3.3
2584.02	<i>Ovis aries</i>	sheep	L humerus	adult	-21.0	5.5	3.3
2361	<i>Ovis aries</i>	sheep	L humerus	adult	-22.0	8.5	3.2
803.2	<i>Bos taurus</i>	cattle	innominate	perinatal	-21.7	6.6	3.4
1258.03	<i>Bos taurus</i>	cattle	innominate	perinatal	-21.7	5.2	3.3
284	<i>Bos taurus</i>	cattle	innominate	perinatal	-21.0	6.4	3.3
4610	<i>Bos taurus</i>	cattle	rib	adult	-21.4	5.4	3.2
90.01	<i>Bos taurus</i>	cattle	rib	adult	-21.5	5.1	3.3
1050	<i>Bos taurus</i>	cattle	rib	adult	-21.6	5.4	3.3
4500.04?	<i>Sus domesticus</i>	pig	ulna	juvenile	-22.1	6.7	3.3
5004.11	<i>Sus domesticus</i>	pig	ulna	adult	-20.4	8.2	3.2
4580.16	<i>Sus domesticus</i>	pig	ulna	infant	-21.8	8.3	3.3
4526.01	<i>Canis domesticus</i>	dog	R femur	adult	-20.6	9.1	3.2
1345.04	<i>Cervus elaphus</i>	red deer	L humerus	adol	-20.9	5.3	3.3

175  
176 Table 1. Quanterness fauna sample details and results of  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  analysis.  
177

178 The six cattle values cluster tightly at  $-21.5 \pm 0.3\text{‰}$  and  $5.7 \pm 0.6\text{‰}$  for  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$   
179 values, respectively. The single red deer value is comparable ( $-20.9\text{‰}$ ,  $5.3\text{‰}$ ). The  
180 three pigs analysed exhibit similar  $\delta^{13}\text{C}$  values ( $-21.4 \pm 0.9\text{‰}$ ) but are significantly  
181 elevated above cattle and deer in  $\delta^{15}\text{N}$  ( $7.7 \pm 0.9\text{‰}$ ), reflecting their more omnivorous  
182 diets. The single domestic dog in the study yielded values of  $-20.6\text{‰}$  and  $9.1\text{‰}$  for  $\delta^{13}\text{C}$   
183 and  $\delta^{15}\text{N}$ , respectively.

184  
185 The range of  $\delta^{13}\text{C}$  values for sheep ( $-22.3$  to  $-16.9\text{‰}$ ) is considerably wider than that  
186 seen in the other species. However, as noted below, the lowest values may date to the  
187 medieval period. More interesting are three of the juvenile sheep aged 0-3 months  
188 occupying the higher end of the range: including the other two animals in this age class  
189 (excluding the lowest value), this group averages  $-18.6 \pm 1.3\text{‰}$  for  $\delta^{13}\text{C}$  and  $8.6 \pm 0.8\text{‰}$   
190 for  $\delta^{15}\text{N}$  values, compared to  $-20.9 \pm 0.35\text{‰}$  and  $5.9 \pm 0.6\text{‰}$  for the five animals older  
191 than ca. six months (i.e., with fused distal epiphyses). The foetal sample is  
192 indistinguishable from the adults in its  $\delta^{13}\text{C}$  value ( $-20.8\text{‰}$ ), as would be expected, but  
193 has a high  $\delta^{15}\text{N}$  value ( $8.3\text{‰}$ ), considerably higher than seen in the adult animals. While



194 this would be unexpected in humans, it has been previously observed in sheep, and  
 195 may relate to differing placental systems (Balasse 1999: Appendix II, and pers. comm.).  
 196 As expected, the young lambs (0-3 months) are also enriched in  $^{15}\text{N}$  compared to the  
 197 older lambs and adult sheep (Table 2).

198

199 Figure 2. Plot of faunal and human  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  results from Quanterness (human  
 200 data from Schulting *et al.* 2010).

201

Species	$\delta^{13}\text{C}$	$\pm$	$\delta^{15}\text{N}$	$\pm$	<i>n</i>
sheep					
all	-20.3	1.6	7.8	1.5	14
foetal	-20.8	-	8.3	-	1
0-3 mon	-18.6	1.3	8.6	0.8	5
> 6 mon	-20.9	0.3	5.9	0.6	5
medieval?	-22.2	0.2	9.2	0.6	3
cattle	-21.5	0.3	5.7	0.6	6
all	-21.5	0.4	5.7	0.6	6
perinatal	-21.5	0.4	6.1	0.8	3
adult	-21.5	0.1	5.3	0.2	3
pig	-21.4	0.9	7.7	0.9	3
dog	-20.6	-	9.1	-	1
red deer	-20.9	-	5.3	-	1

202

203 Table 2. Summary statistics for Quanterness faunal  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  measurements. The  
 204 sheep identified as likely of medieval date (see Table 3) are included in the total but  
 205 treated separately in the age categories.

206

207

Cat no.	Species	Age	Lab code	$^{14}\text{C}$ yrs	$\pm$	cal BC (95.4%)		$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	C:N	%mar
4084.2	<i>Ovis Aries</i>	0-3 mon	UBA-18429	4499	32	3084	2866	-16.9	9.6	3.3	46
146.07	<i>Ovis Aries</i>	0-3 mon	UBA-18428	4197	34	2864	2495	-18.6	8.7	3.3	27
2491.04	<i>Ovis Aries</i>	0-3 mon	UBA-18426	3855	29	2286	1981	-17.8	8.3	3.3	36
249.11	<i>Ovis Aries</i>	adult	UBA-18425	3367	31	1632	1427	-20.7	6.9	3.3	3
4029.07	<i>Ovis Aries</i>	0-3 mon	UBA-18427	908	25	AD 1168-1300		-22.2	9.6	3.3	0
4580.16	<i>Sus domesticus</i>	infant	UBA-18432	4302	37	3014	2880	-21.8	8.3	3.3	0
1345.04	<i>Cervus elaphus</i>	adol.	UBA-18431	3785	28	2196	1939	-20.9	5.3	3.3	1
1258.03	<i>Bos taurus</i>	perinatal	UBA-18433	3649	24	2009	1755	-21.7	5.2	3.3	0
4526.01	<i>Canis domesticus</i>	adult	UBA-18430	3466	24	1743	1535	-20.6	9.1	3.2	4

208

209 Table 3. Results of  $^{14}\text{C}$  dating. Mixed marine-terrestrial curves are used for the three  
 210 young sheep with significantly elevated  $\delta^{13}\text{C}$  values (Reimer *et al.* 2013).

211

212 The radiocarbon dating results range widely, from  $4499 \pm 32$  BP (UBA-18429) to  $908 \pm$   
 213  $25$  BP (UBA-18427) (Table 3). Calibration of the dates for three young lambs – including  
 214 the earliest result in the series – is complicated by their elevated  $\delta^{13}\text{C}$  values suggesting

215 that they consumed significant amounts of marine foods. The use of a mixed  
216 marine/terrestrial curve is therefore required, with ‘%marine’ being calculated using a  
217 simple linear extrapolation between marine and terrestrial bone collagen endmembers  
218 of -12‰ and -21‰, respectively (Barrett and Richards 2004; Richards and Hedges  
219 1999; Schulting and Richards 2009) (Table 2). The validity of these endmembers has  
220 been repeatedly confirmed on studies of archaeological marine and terrestrial fauna  
221 from western and northern Scotland (Charlton *et al.* 2016; Montgomery *et al.* 2013;  
222 Mulville *et al.* 2009; 2013; Richards *et al.* 2006). The estimate is assumed to have an  
223 uncertainty of  $\pm 10\%$ , included in the model (OxCal 4.2). A local  $\Delta R$  of  $48 \pm 47$  years has  
224 been used, based on the four nearest datapoints in Calib’s Marine Reservoir  
225 Corrections Database (<http://calib.qub.ac.uk/marine/>). No correction has been applied  
226 for cases in which the estimated ‘%marine’ is less than 5%, since the contribution of any  
227 marine protein is uncertain at best.

228

229 Once calibrated, three results fall within the early to mid-third millennium cal BC,  
230 conventionally designated as Late Neolithic in a British context, although the first  
231 century or so of the third millennium is probably better understood as culturally ‘Middle  
232 Neolithic’ in the sense that passage tombs still featured prominently on the mortuary  
233 landscape (Schulting *et al.* 2010). Three results fall within the late third to early second  
234 millennium, towards the end of the Chalcolithic in one case and within the Early Bronze  
235 Age in the other two. Two results lie within the mid- to late second millennium, on the  
236 border between the Early and Middle Bronze Age. Finally, the latest determination  
237 within the group is clearly an outlier, falling within the medieval or late Norse period, cal  
238 AD 1168–1300. This particular sample, a young lamb, was selected as one of three  
239 showing unusually low  $\delta^{13}\text{C}$  values, of -22.0‰ or less (Table 1). On this basis we  
240 suspect, though cannot demonstrate, that all three samples may be medieval in date.

241

242 Figure 3. OxCal 4.2 (Bronk Ramsey 2013) plot of calibrated faunal dates from  
243 Quanterness (excluding UBA-18427,  $908 \pm 25$  BP).

244

## 245 **4. Discussion**

### 246 *4.1 Implications for animal management*

247 Significantly elevated  $\delta^{13}\text{C}$  values for three of the 14 sheep analysed from Quanterness  
248 indicate the consumption of seaweed (for a summary of  $\delta^{13}\text{C}$  measurements made on  
249 seaweeds from across the UK, see Balasse *et al.* 2005: table 1). There are no other  
250 possibilities for enriched  $^{13}\text{C}$  resources on the archipelago at this time, nor is there any  
251 issue with the identification of the skeletal elements (left humeri) selected for analysis:  
252 they are definitely ovicaprids. Based on the linear extrapolation used to correct their  
253 radiocarbon dates for the marine reservoir effect, it is estimated that these three lambs  
254 obtained between ca. 27% and 46% of their dietary protein from seaweeds, albeit  
255 indirectly since they would be too young to be grazing. The results join previous  
256 research that has identified a small number of sheep from prehistoric sites on Orkney  
257 with elevated  $\delta^{13}\text{C}$  values similarly indicating the consumption of seaweeds. Two  
258 neonatal lambs from Holm of Papa Westray North (HPWN) are represented by  
259 measurements on bone collagen, initially identified through radiocarbon dating (Bronk  
260 Ramsey *et al.* 2002; Schulting *et al.* 2004), with one sample re-analysed specifically for  
261 palaeodietary reconstruction (Schulting and Richards 2009). One of these neonates  
262 yielded extremely elevated  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of -12.8‰ and 12.6‰, respectively.  
263 Essentially, this can be considered a 100% marine diet. However, given that this animal  
264 did not survive past infancy, this diet may have been *in extremis* on the part of its  
265 mother rather than the result of an intentional management strategy. One previously  
266 suggested possibility is that this sheep was part of a feral flock – or even just a few  
267 animals – abandoned on the islet, though this in itself may be seen as part of a  
268 management strategy (Balasse and Tresset 2009; Schulting and Richards 2009: 72).  
269

270 The animals showing high  $\delta^{13}\text{C}$  values also tend to be elevated in  $\delta^{15}\text{N}$ . While this may  
271 partly reflect the predictable enrichment caused by the nursing effect (Jenkins *et al.*  
272 2001), such high values must be related to the considerably  $^{15}\text{N}$ -enriched content of  
273 seaweeds compared to grasses (Caumette *et al.* 2007). This is supported by the strong  
274 positive correlation between  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values ( $r^2 = 0.767$ ,  $p < 0.001$ ) seen in the  
275 Quanterness sheep (excluding the three cases thought to be medieval). Extending this  
276 analysis to include the sheep from HPWN and other Neolithic and Bronze Age sites on  
277 Orkney (Jones and Mulville 2016) reduces the strength of correlation ( $r^2 = 0.609$ ,  $p <$   
278 0.001) but only because of the greater scatter at the low end of the scale for both

279 elements (Figure 4). It is worth noting that, while the sheep/goat data presented by  
280 Jones and Mulville (2016: table 2) do not include any definite examples of seaweed  
281 consumption (average  $-20.8 \pm 0.6\text{‰}$ , maximum  $-19.7\text{‰}$ ,  $n = 26$ ), three animals do have  
282 values above  $-20\text{‰}$ . Moreover, there is a slight but significant positive correlation  
283 between  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values ( $r^2 = 0.127$ ,  $p = 0.045$ ), which may plausibly reflect some  
284 marine influence (cf. Richards and Hedges 1999). As Jones and Mulville (2012: 670;  
285 see also Jones *et al.* 2012) note, it is possible that this is the result of foreshore grazing  
286 on terrestrial plants enriched in  $^{13}\text{C}$  and  $^{15}\text{N}$  due to salinity effects (Heaton 1987; Britton  
287 *et al.* 2008), rather than the consumption of seaweed. However, this cannot account for  
288 the more elevated values seen in the young animals from Quanterness and HPWN. The  
289 absence of comparably elevated  $\delta^{13}\text{C}$  values in the larger number of samples analysed  
290 by Jones and Mulville can be explained by their decision to focus only on mature  
291 animals, to avoid complications introduced by nursing effects (2012: 668). While entirely  
292 understandable, this creates ambiguity in the interpretation of the adult values, and  
293 could mask periods of significant consumption of marine resources.

294

295 Figure 4. Plot of bone collagen  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  measurements on sheep/goat from  
296 Neolithic and Bronze Age Orkney (data: this paper; Jones and Mulville 2016; Schulting  
297 and Richards 2009). The three squares identify low values thought to be medieval  
298 intrusions, and are not included in the regression.

299

300 Orcadian Neolithic and Bronze Age cattle, by contrast, show no correlation between  
301  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values ( $r^2 = 0.059$ ,  $p = 0.158$ ) (Figure 5). This is consistent with results  
302 from tooth enamel carbonate studies on cattle that have found no evidence for seaweed  
303 consumption (Balasse *et al.* 2006; Towers *et al.* 2016), despite their social and  
304 economic importance on Orkney from the Neolithic onwards. This may reflect the more  
305 adaptable gut physiology of sheep, in particular their tolerance of the high levels of  
306 arsenic found in seaweeds (Caumette *et al.* 2007; Feldman *et al.* 2000). However, this  
307 cannot be the entire explanation, since supplementing cattle fodder with seaweed is  
308 well attested historically (Hallson 1964; Makkar *et al.* 2016; Martin 1703). Perhaps the  
309 greater value of cattle – and hence greater investment in them – meant that the bulk of  
310 the winter hay and chaff from  $\text{C}_3$  plants was reserved for them.

311

312 Figure 5. Plot of bone collagen  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  measurements of humans and fauna  
313 from Neolithic and Bronze Age Orkney (data: this paper; Jones and Mulville 2016;  
314 Schulting et al. 2010; Schulting and Richards 2009).  
315

316 A number of other examples interpreted as indicative of seaweed consumption in  
317 Neolithic Orkney derive from sequential  $\delta^{13}\text{C}$  measurements of tooth enamel from Point  
318 of Cott and HPWN, dating to ca. 3000 cal BC (Barber 1997; Ritchie 2009) and hence  
319 being contemporary with the earliest results from Quanterness. This method has the  
320 distinct advantage of providing resolution on an intra-annual seasonal level through  
321 comparison with accompanying  $\delta^{18}\text{O}$  measurements (Balasse *et al.* 2005; 2006; 2009;  
322 Balasse and Tresset 2009). At Point of Cott, one of three sheep second molars  
323 analysed presented a peak indicating a significantly  $^{13}\text{C}$ -enriched diet for part of the  
324 tooth mineralization period (Balasse *et al.* 2009). By contrast, all 12 sheep molars (M2s  
325 and M3s, representing the first and second years of life, respectively – Milhaud and  
326 Nezit 1991) analysed from HPWN recorded peaks in  $\delta^{13}\text{C}$  values during the colder  
327 season as represented by lower  $\delta^{18}\text{O}$  values, though not as low as would be expected  
328 for animals drinking from terrestrial water sources in the winter (Figure 6a) (Balasse *et*  
329 *al.* 2006; Balasse and Tresset 2009). Balasse and colleagues reasonably inferred from  
330 this that the HPWN sheep consumed fresh seaweed on the seashore (and ingested the  
331 oceanic water contained therein), rather than being foddered in the winter with dried  
332 seaweed collected specifically for this purpose (a practice for which there are historical  
333 references). The high enamel  $\delta^{13}\text{C}$  values suggest that the winter diet consisted of  
334 approximately 45-70% seaweed (Balasse *et al.* 2006: 173), so that the animals must  
335 still have had access to terrestrial vegetation. By contrast, none of the 11 sheep molars  
336 analysed from the nearby settlement of Knap of Howar, dating to a few centuries earlier  
337 – to ca. 3600 cal BC – show enriched  $\delta^{13}\text{C}$  values (Figure 6b). As Balasse *et al.* (2006)  
338 note, this could place the origins of the practice of seaweed foddering on Orkney  
339 towards the end of the fourth millennium BC. The Quanterness data support the  
340 consumption of seaweed by sheep dating to the same time period, but in the absence of  
341 earlier animals from the site cannot shed further light on this issue.

342

343 Figure 6. Plot of sequential enamel  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  measurements on sheep third molars  
344 from a) Holm of Papa Westray North, and b) Knap of Howar (Balasse and Tresset  
345 2009).

346  
347 The modern and historically attested lambing season on Orkney takes place relatively  
348 late, from late April to May/June (Balasse *et al.* 2006). Given a five month gestation  
349 period, the foetus would be developing *in utero* from November to birth from late April.  
350 The scarcity of grass over the winter months would make this period suited to the use of  
351 seaweed as alternative fodder. Assuming that this pattern is broadly comparable to that  
352 in the mid-Holocene (and there is no reason to think otherwise, given the absence of  
353 significant climate change in the intervening period), then lambing would most likely  
354 take place on the newly revitalised spring pastures. This also seems more probable  
355 from the point of view of the safety of the newborn lambs, which might be susceptible to  
356 being swept out to sea in the intertidal zone. Indeed, this is the current and historically  
357 documented practice on North Ronaldsay, with females being moved from the shore  
358 onto inland pastures for lambing (Fenton 1978; Hansen *et al.* 2003).

359  
360 The proportion of seaweed in the diet of the animals at HPWN suggested by the enamel  
361  $\delta^{13}\text{C}$  values (45-70%) would be expected to result in bone collagen values for the  
362 newborn lambs of ca. -14.7‰ to -17.0‰. While we cannot assume similar animal  
363 management practices between the two sites, it can be noted that, while the observed  
364 values for lambs in the 0-3 month age class at Quanterness do retain a 'marine  
365 influence', they are lower than this, ranging from -16.9‰ to -19.9‰. But, following on  
366 from the above discussion, newborn lambs would be nursing on milk produced by ewes  
367 feeding on new grass. Because of the rapid growth seen in the skeletons at this age,  
368 their bone collagen  $\delta^{13}\text{C}$  values would change relatively rapidly, so that after three  
369 months they might very well fall within the observed range. The few older lambs that  
370 have been measured show no influence of seaweed. It is surprising that both they and  
371 the adult animals show so little input into their bone collagen of the winters spent, by at  
372 least some animals, during the first and second years of life consuming significant  
373 amounts of seaweed, as indicated by the sequential enamel measurements on second  
374 and third molars from Point of Cott and HPWN. While we cannot guarantee that any of  
375 the same animals were measured in the enamel and the bone collagen studies, given  
376 that *all* 12 molars analysed at HPWN showed seasonal consumption of seaweed, we  
377 would expect to find more evidence of this in the collagen of older animals, though

378 admittedly there are only two measurements on adult sheep currently available from the  
379 site (Schulting and Richards 2009). That it was not detected at Knap of Howar is not  
380 surprising, since the enamel results did not find any evidence for the practice there.

381  
382 By contrast, bone collagen of modern adult sheep on North Ronaldsay, confined to the  
383 seashore for most of the year, have the expected high  $\delta^{13}\text{C}$  values averaging ca. -13‰  
384 (Ambers 1990). While the adolescent and adult sheep from Quanterness do have  
385 significantly higher average  $\delta^{13}\text{C}$  values than the cattle from the site (-20.9‰ vs. -  
386 21.5‰, Student's t-test,  $t = 3.18$ ,  $p = 0.011$ ), the difference is only 0.6‰. This is hard to  
387 reconcile, though of course the same animals are not being measured in the enamel  
388 and collagen studies, nor indeed are they from the same site, though they are  
389 approximately contemporary and in relatively close proximity to one another. (That  
390 measurements on enamel reflect whole diet while collagen measurements are biased  
391 towards dietary protein (Ambrose and Norr 1993) should not be an issue here, since  
392 seaweeds and grasses appear to have similar protein content and digestibility (Hansen  
393 *et al.* 1991)). Statistically significant differences of a similar order were identified  
394 between sheep/goat and cattle  $\delta^{13}\text{C}$  values by Jones and Mulville (2016: 668-669) for  
395 Neolithic, Bronze Age and Iron Age Orkney, as well as for the Bronze Age of the  
396 Western Isles (though not the Neolithic or the Iron Age). However, as noted above, this  
397 could relate in part to coastal grazing rather than episodic high seaweed consumption.  
398 Sequential enamel  $\delta^{13}\text{C}$  analyses of sheep and cattle from the Iron Age and Norse  
399 periods in Orkney have found no evidence for seaweed foddering (Mainland *et al.*  
400 2016). Ambers (1990) also found no evidence for the practice in prehistoric Orkney, in a  
401 study using  $\delta^{13}\text{C}$  measurements on bone collagen.

402  
403 Given that only very young animals show a distinct 'marine'  $\delta^{13}\text{C}$  signal, it is possible  
404 that foddering pregnant ewes with seaweed was in fact a last resort when terrestrial  
405 resources failed, so that young animals born when their mothers had been on this diet  
406 were more likely to die, and hence retain elevated  $\delta^{13}\text{C}$  values in their bone collagen.  
407 This is reminiscent of a recent study of sequential human dentine isotope  
408 measurements from a Neolithic site on the small island of West Voe, Shetland, showing  
409 that those individuals with periodic high use of marine resources were more likely to die

410 young (Montgomery *et al.* 2013). In both cases the burial assemblage is intrinsically  
411 biased by differential survivorship – the classic ‘osteological paradox’ (Wood *et al.*  
412 1992).

413

#### 414 *4.2 Implications for Neolithic human diet*

415 The evidence for seaweed consumption by pregnant ewes, seen most clearly in  
416 newborn lambs, raises questions regarding their impact on human diets. Essentially, a  
417 ‘marine’ isotopic signal could be introduced through the consumption of a terrestrial  
418 mammal. As discussed in Schulting and Richards (2009), this is an alternative  
419 explanation to the direct exploitation of marine resources for the slight elevation in the  
420  $\delta^{13}\text{C}$  values observed in human bone collagen from the chambered tomb of HPWN.  
421 However, this slight elevation was being considered in comparison with the human  
422 results from Quanterness, where there seems to be no clearly detectable impact on  
423  $\delta^{13}\text{C}$  values of the use of marine resources ( $-20.6 \pm 0.3\text{‰}$ ), whether direct or indirect  
424 (Figure 2). Following the discussion above, this is perhaps not surprising. Only a small  
425 number of very young lambs show significantly enriched carbon and nitrogen isotope  
426 values. Once on grass, which likely was the case from birth, their flesh values would  
427 very quickly become depleted in  $^{13}\text{C}$ , reflecting this dietary change. The bone collagen  
428 of adult sheep appears to show surprisingly little impact of seaweed consumption,  
429 though interpretation is complicated by the bone and tooth enamel analyses being  
430 conducted on different animals.

431

432 Another finding to emerge from this study is that the use of direct radiocarbon dating of  
433 at least a sample of faunal remains is essential in those cases where the  
434 contemporaneity of the faunal assemblage cannot be securely assigned to a phase on  
435 archaeological/stratigraphic grounds. This is highlighted here by the fact that only three  
436 of the nine determinations returned results coeval with the use of the chambered tomb  
437 for burial in the Late Neolithic. Despite the presence of intrusive fauna, it is interesting to  
438 note that the early dates include one of the three pigs represented in the study. Pigs are  
439 relatively rare in Orcadian Neolithic faunal assemblages, and this can be explained by  
440 the limited availability of natural habitat suited to their foraging preferences (i.e.,  
441 woodland). Hence, they would likely need to be supplied with food at least some of



442 which would be suitable for humans, and would thus be in competition (McCormick and  
443 Buckland 2003: 91; Schulting 2013). A small number of pigs may have been fed on  
444 domestic refuse and crop waste. Pigs can also be fed marine foods (seaweed, shellfish,  
445 fish), but, surprisingly, there is no isotopic evidence for this in Orcadian prehistory. It is  
446 not until the Iron Age that we see convincing evidence for this practice, not in Orkney,  
447 but in the Western Isles (Jones and Mulville 2016: figure 13).

448  
449 Three faunal samples can be placed within the Chalcolithic/Early Bronze Age, while  
450 another two lie at the Early-Middle Bronze Age border. This chronology is considerably  
451 more extended than that for the human remains (Schulting *et al.* 2010). What is less  
452 clear is the nature of the deposition of the faunal remains post-dating the use of the  
453 tomb for burial. The lack of other finds (e.g., pottery) dating to the Bronze Age suggests  
454 that the deposition may not have been intentional, or at least not ritual, but rather that  
455 animals sought shelter in the monument and died there naturally, or were disposed of  
456 there by Bronze Age farmers. A re-examination of the fauna for butchery marks might  
457 help in choosing between these alternatives, although the mixed nature of the deposits  
458 means that an extensive programme of radiocarbon dating would be required to identify  
459 the Bronze Age component. Finally, one juvenile sheep dates to the medieval period,  
460 known as the late Norse period on Orkney. The latter is particularly significant, since it is  
461 one of a group of three animals with notably lower than average  $\delta^{13}\text{C}$  values at the site.  
462 Assuming that the other two animals are also later intrusions, it is clear that using these  
463 results for formal palaeodietary modelling of the human isotopic results could be highly  
464 misleading. If it is confirmed that all three are late, a question is raised over why they  
465 should be depleted in  $^{13}\text{C}$  during this period.

466

## 467 **5. Conclusions**

468 The faunal  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  data from Quanterness provide further evidence for the  
469 consumption of seaweeds, probably by pregnant ewes, on Orkney from the late fourth  
470 millennium BC, with additional cases in both the early and late third millennium,  
471 extending the temporal range of this practice into the Chalcolithic. However, the extent  
472 to which this was part of an ongoing, intentional management strategy remains unclear.  
473 An alternative scenario is that the use of seaweed was a fallback strategy in years

474 where insufficient terrestrial grasses were available to last the winter. Only a very  
475 minimal increase in  $\delta^{13}\text{C}$  values can be found in the bone collagen of older lambs and  
476 adult animals, so that little impact on human diets would be expected, consistent with  
477 what has been observed in the previously published human results from Quanterness  
478 (Schulting et al. 2010).

479  
480 It is clear that further research is required to better understand the origins and  
481 implications of the practice of seaweed foddering in northern Europe. Enamel studies  
482 have indicated recurrent substantial consumption of seaweed in the winter by  
483 adolescent and adult sheep, yet the impact on bone collagen is minimal. However,  
484 these studies have rarely been joined up, and have been carried out on different  
485 individuals often from different sites. Clearly there is scope for a more coordinated  
486 effort, which could also include dental microwear analysis (e.g., Mainland *et al.* 2016),  
487 which has been shown to be capable of distinguishing between seaweed and grass  
488 grazing sheep (Mainland 2000). There is currently an impression that the practice did  
489 not continue into later prehistory, suggesting that perhaps it was not particularly  
490 successful as a management strategy, at least until revived in the nineteenth century on  
491 North Ronaldsay. It should not be assumed that once a new farming practice appears, it  
492 will continue to be used thereafter. Future research will need to focus on immature  
493 animals and sequential sampling of both enamel and dentine.

494

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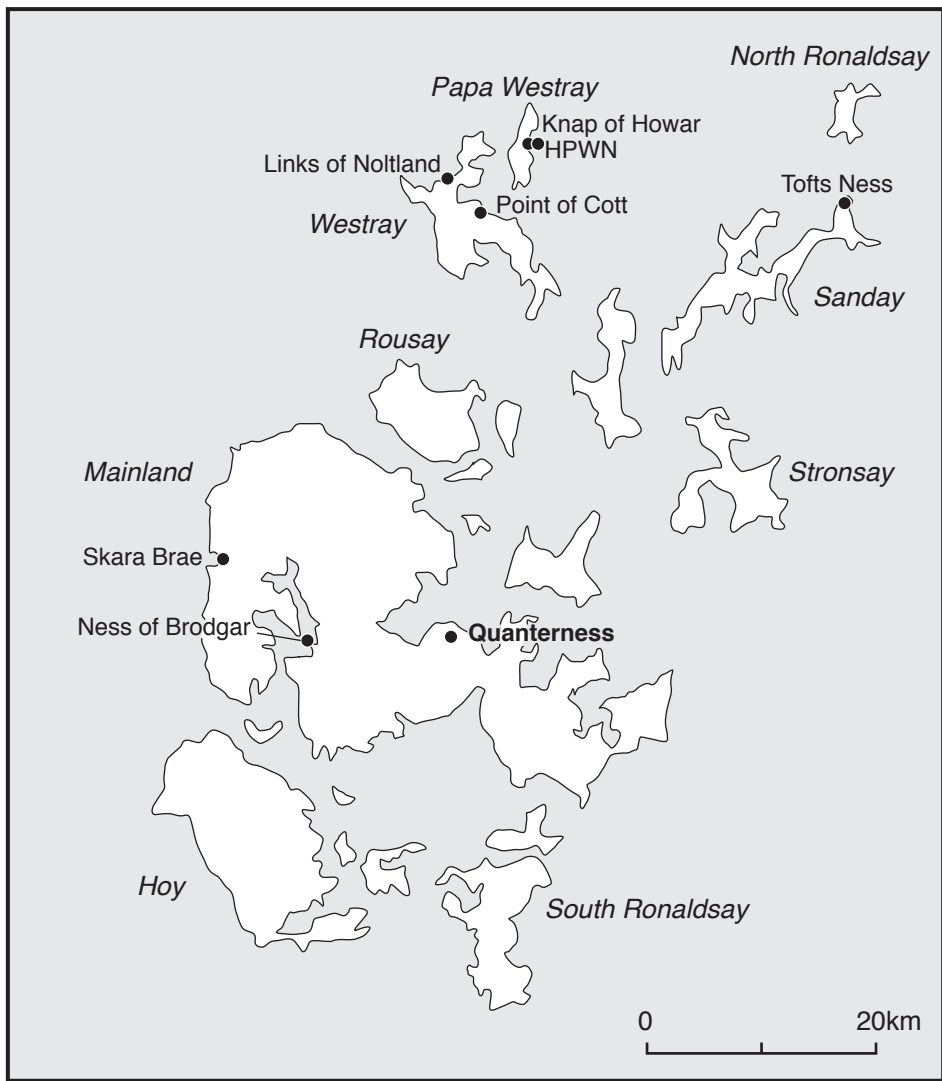
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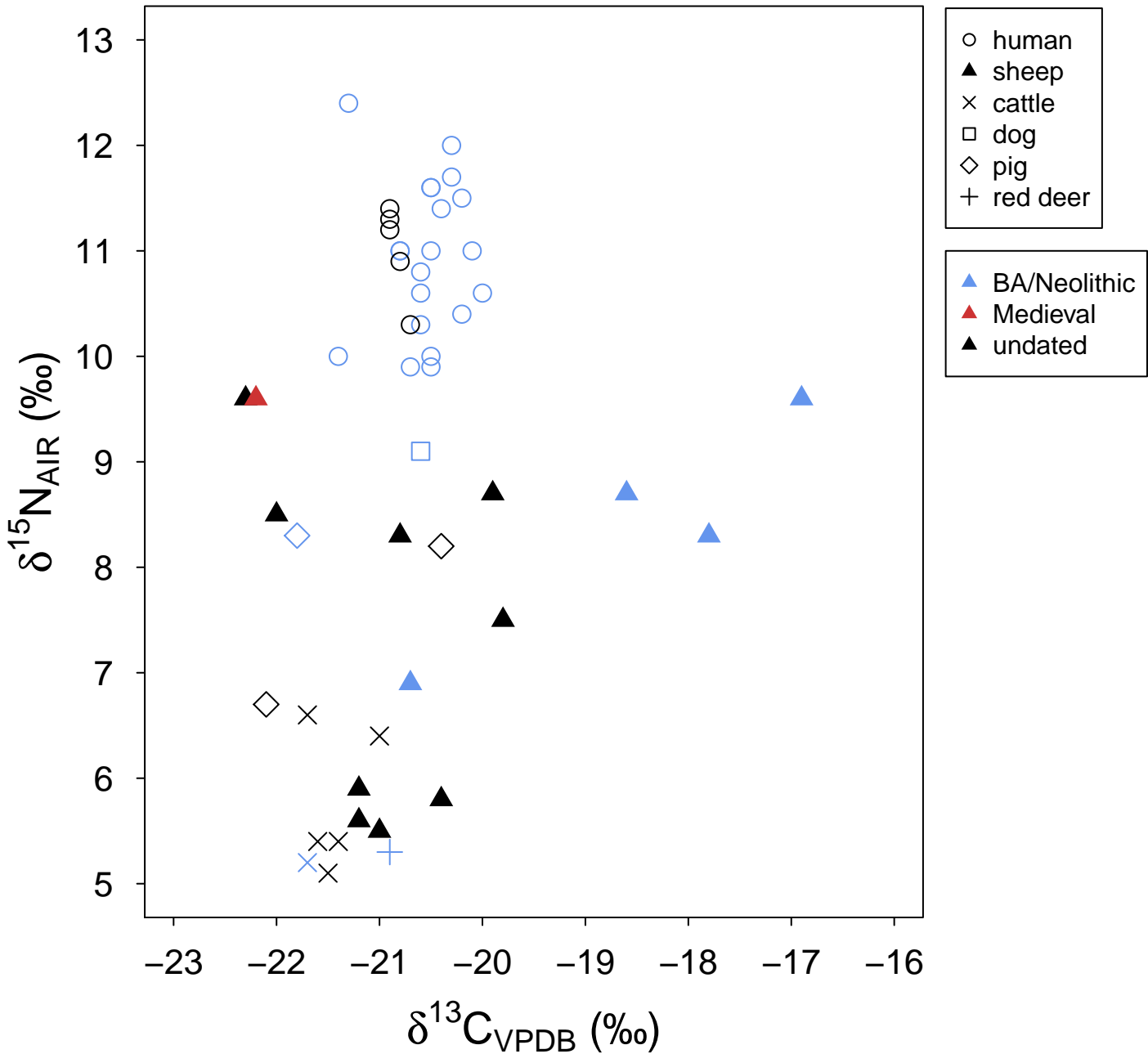
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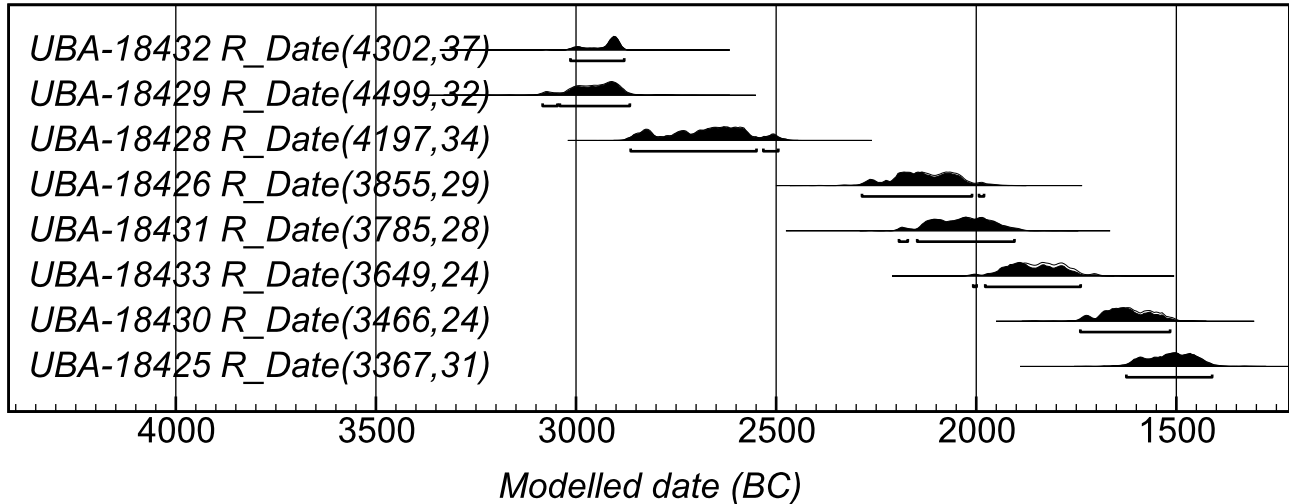
739 **Figures and Tables**

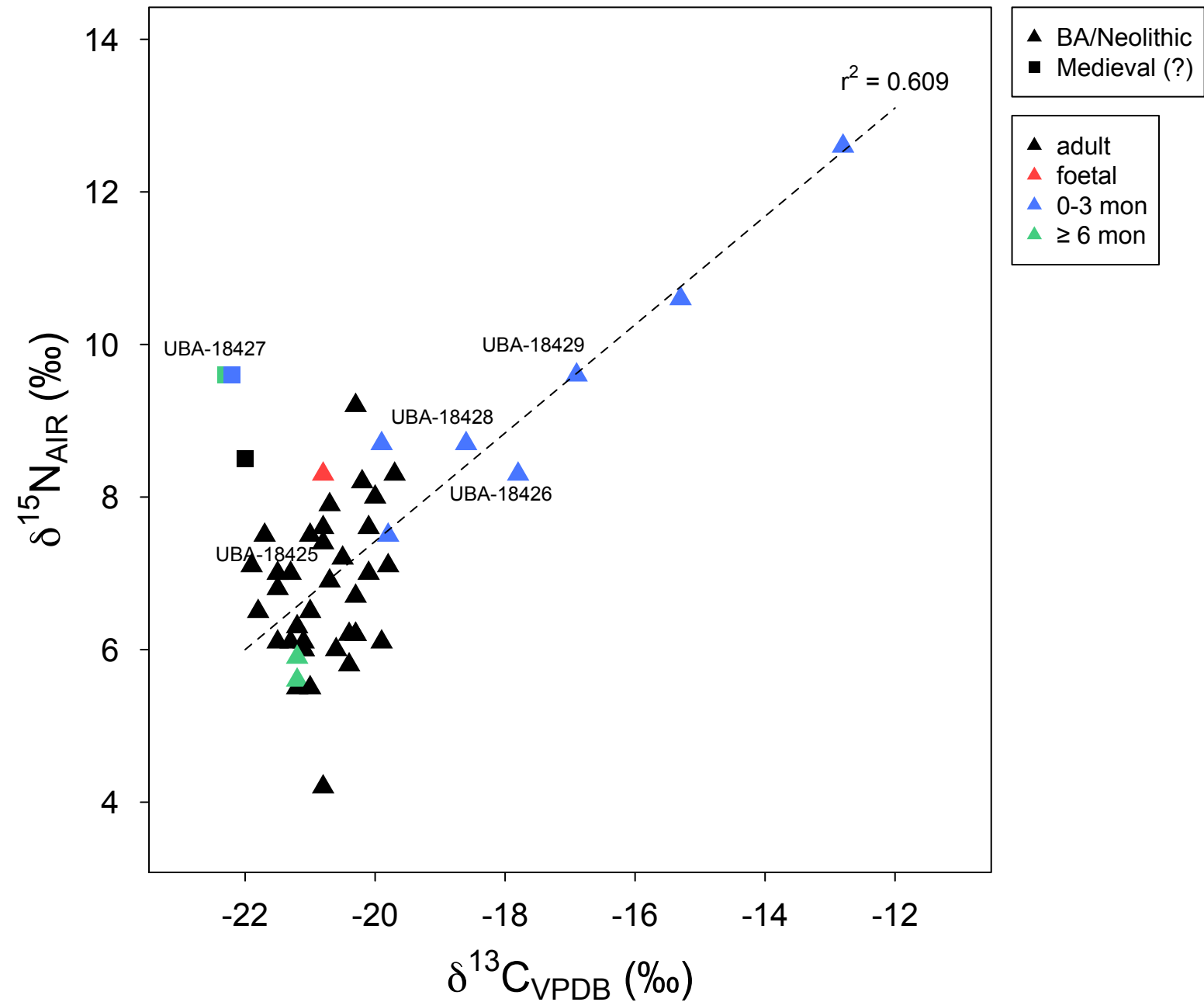
- 740
- 741 Figure 1. Map of Orkney showing locations mentioned in the text.
- 742
- 743 Figure 2. Plot of  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  results from Quanterness
- 744
- 745 Figure 3. OxCal 4.2 (Bronk Ramsey 2013) plot of calibrated faunal dates from
- 746 Quanterness (excluding UBA-18427,  $908 \pm 25$  BP).
- 747
- 748 Figure 4. Plot of bone collagen  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  measurements on sheep/goat from
- 749 Neolithic and Bronze Age Orkney (data: this paper; Jones and Mulville 2016; Schulting
- 750 and Richards 2009). The three squares identify low values thought to be medieval
- 751 intrusions, and are not included in the regression.
- 752
- 753 Figure 5. Plot of bone collagen  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  measurements on humans and fauna
- 754 from Neolithic and Bronze Age Orkney (data: this paper; Jones and Mulville 2016;
- 755 Schulting *et al.* 2010; Schulting and Richards 2009).
- 756
- 757 Figure 6. Plot of sequential enamel  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  measurements on sheep third molars
- 758 from a) Holm of Papa Westray North, and b) Knap of Howar (Balasse and Tresset
- 759 2009).
- 760
- 761
- 762 Table 1. Quanterness fauna sample details and results of  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  analysis.
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- 764 Table 2. Summary statistics for Quanterness fauna  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  results.
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- 766 Table 3. Results of  $^{14}\text{C}$  dating. Mixed marine-terrestrial curves are used for the three
- 767 juvenile sheep with significantly enriched  $^{13}\text{C}$  (Reimer *et al.* 2013).













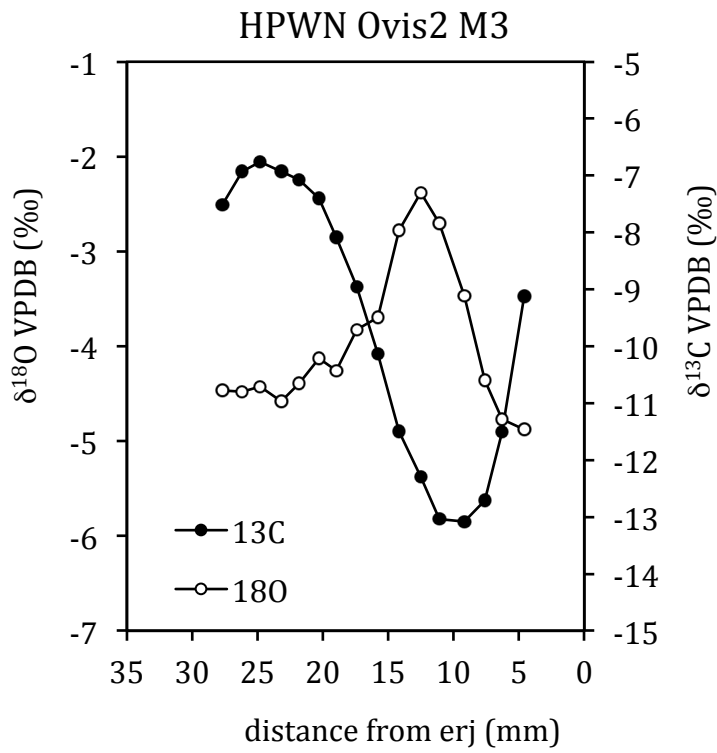


Figure 6a

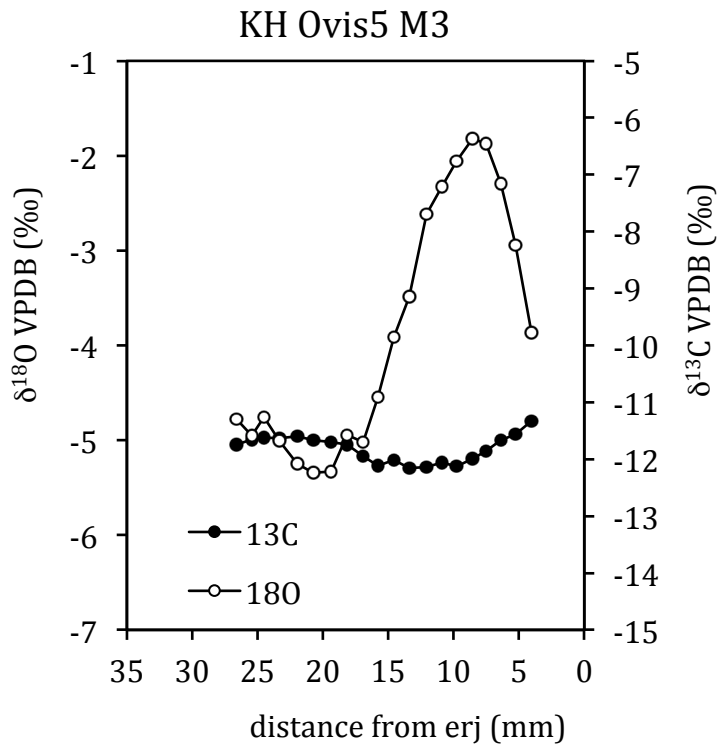


Figure 6b