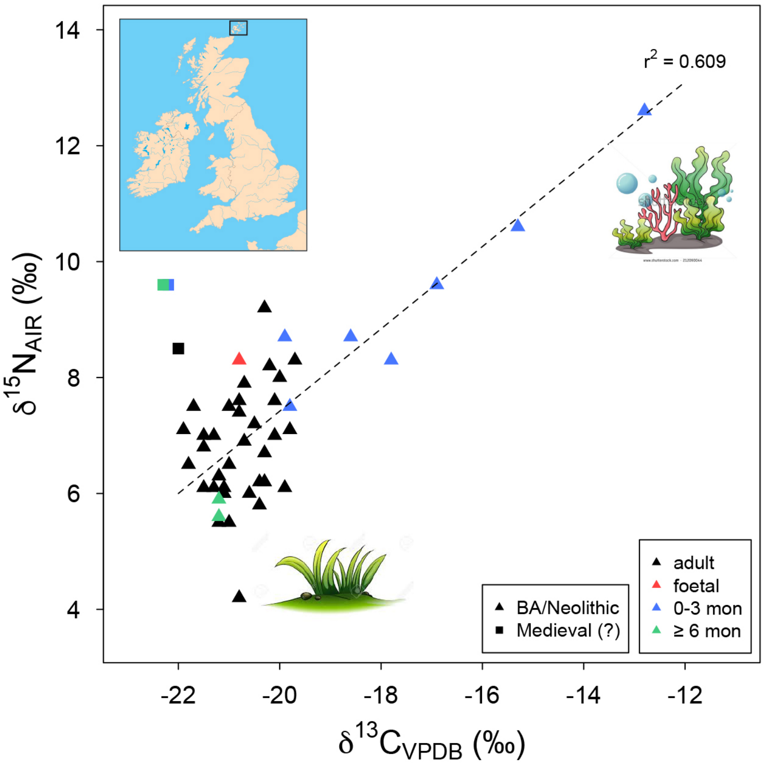
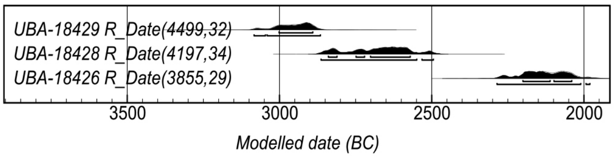

r^2 = 0.609
14
12
10
8
6
4
$\delta^{15}N_{AIR}$ (‰)
-22
-20
-18
-16
-14
-12
$\delta^{13}C_{VPDB}$ (‰)
▲ BA/Neolithic
■ Medieval (?)
▲ adult
▲ foetal
▲ 0-3 mon
▲ ≥ 6 mon


UBA-18429 R_Date(4499,32)
UBA-18428 R_Date(4197,34)
UBA-18426 R_Date(3855,29)
3500
3000
2500
2000
Modelled date (BC)

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 δ^{13}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 δ^{13}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

1. Introduction

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

2. Overview of stable carbon and nitrogen isotope analysis

Measurements of bone collagen stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) values are frequently used in archaeology to investigate the major sources of dietary protein (Ambrose and Norr 1993; Lee-Thorp 2008). The values obtained via isotope ratio mass spectrometry (IRMS) provide a relatively long-term average of primarily protein intake, though the exact length of time represented will depend on the rate of remodeling of the sampled bone, but will always be more rapid in young, growing animals. The ratios of stable C and N isotopes incorporated into animal tissues are driven by the isotopic composition of major dietary sources. Marine organisms, including seaweed, shellfish, fish and sea mammals, are enriched in ^{13}C relative to ^{12}C due to the fact that the ocean serves as a sink for the heavier isotope (Boutton 1991; Sharp 2007). As a result, organisms obtaining a significant proportion of their dietary protein from marine foods will exhibit higher δ^{13}C values (ca. -12 ± 1‰) than those subsisting solely on C_3 terrestrial foods, which provide lower values (ca. -21 ± 1‰) for bone collagen (Richards and Hedges 1999). The consumption of C_4 plants such as maize and millet would result in even higher bone collagen values than the consumption of marine foods, but as no such plants were found in northwest Europe during the study period, they need not be considered here.

Stable nitrogen isotope ratios are used to investigate trophic levels. There is a variable but broadly predictable increase of ca. 3–5‰ between dietary item and consumer tissue for each step in the food chain (Ambrose 2000; Caut et al. 2009; Hedges and Reynard 2007; Schoeninger and DeNiro 1984). This range is generally cited for human consumers, and may be towards its lower end for most herbivores. The comparable effect in δ^{13}C is considerably smaller, about 1‰ (Bocherens and Drucker 2003; Lee-Thorp *et al*. 1989). The ocean is also enriched in ^{15}N relative to atmospheric N_2 (defined as 0‰), the latter serving as the ultimate source of nitrogen for terrestrial plants (Peterson and Fry 1987). Thus marine plants will generally have higher δ^{15}N values than most temperate terrestrial plants under natural conditions (i.e., in the absence of anthropogenic input). Furthermore, because marine food webs are considerably more complex (i.e., involve more steps) than terrestrial mammalian food webs, there is scope for much greater trophic level enrichment, such that high-level marine carnivores can exhibit collagen δ^{15}N values of +16‰ or more (Schoeninger and DeNiro 1984). Other factors can also result in ^{15}N enrichment, most notably aridity, but this can safely be excluded from discussions pertaining to Orkney.

3. Materials and Methods

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

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

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

The sheep/goats (henceforth 'sheep') were aged using standards in Moran and O'Connor (1994) and Popkin *et al.* (2012). One complete but very small humerus (greatest length = 35.2mm) is from a foetal lamb far from full term (McDonald *et al.* 1977). Six animals are aged between birth and ca. 3 months based on the lengths of (66-70mm) for three complete humeri, and a comparison of maximum breadth of these specimens against the three incomplete elements. Three further humeri were in the process of fusing distally, placing them at ≥6 months. Finally, four animals are classed as adults based primarily on their size, confirmed by the fully fused proximal humerus in the single complete specimen (>36 months).

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

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

3. Results

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

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

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

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

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

The range of $\delta^{13}C$ values for sheep (-22.3 to -16.9‰) is considerably wider than that seen in the other species. However, as noted below, the lowest values may date to the medieval period. More interesting are three of the juvenile sheep aged 0-3 months occupying the higher end of the range: including the other two animals in this age class (excluding the lowest value), this group averages -18.6 ± 1.3‰ for $\delta^{13}C$ and 8.6 ± 0.8‰ for $\delta^{15}N$ values, compared to -20.9 ± 0.35‰ and 5.9 ± 0.6‰ for the five animals older than ca. six months (i.e., with fused distal epiphyses). The foetal sample is indistinguishable from the adults in its $\delta^{13}C$ value (-20.8‰), as would be expected, but has a high $\delta^{15}N$ value (8.3‰), considerably higher than seen in the adult animals. While this would be unexpected in humans, it has been previously observed in sheep, and may relate to differing placental systems (Balasse 1999: Appendix II, and pers. comm.). As expected, the young lambs (0-3 months) are also enriched in ^{15}N compared to the older lambs and adult sheep (Table 2).

Figure 2. Plot of faunal and human δ^{13}C and δ^{15}N results from Quanterness (human data from Schulting *et al*. 2010).

Species		*δ^{13}C*	±	*δ^{15}N*	±	*n*
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

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

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

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

The radiocarbon dating results range widely, from 4499 ± 32 BP (UBA-18429) to 908 ± 25 BP (UBA-18427) (Table 3). Calibration of the dates for three young lambs – including the earliest result in the series – is complicated by their elevated δ^{13}C values suggesting that they consumed significant amounts of marine foods. The use of a mixed marine/terrestrial curve is therefore required, with '%marine' being calculated using a simple linear extrapolation between marine and terrestrial bone collagen endmembers of -12‰ and -21‰, respectively (Barrett and Richards 2004; Richards and Hedges 1999; Schulting and Richards 2009) (Table 2). The validity of these endmembers has been repeatedly confirmed on studies of archaeological marine and terrestrial fauna from western and northern Scotland (Charlton *et al*. 2016; Montgomery *et al*. 2013; Mulville *et al*. 2009; 2013; Richards et al. 2006). The estimate is assumed to have an uncertainty of ±10%, included in the model (OxCal 4.2). A local ΔR of 48 ± 47 years has been used, based on the four nearest datapoints in Calib's Marine Reservoir Corrections Database (http://calib.qub.ac.uk/marine/). No correction has been applied for cases in which the estimated '%marine' is less than 5%, since the contribution of any marine protein is uncertain at best.

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

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

4. Discussion

4.1 Implications for animal management

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

The animals showing high $\delta^{13}C$ values also tend to be elevated in $\delta^{15}N$. While this may partly reflect the predictable enrichment caused by the nursing effect (Jenkins *et al.* 2001), such high values must be related to the considerably ^{15}N-enriched content of seaweeds compared to grasses (Caumette *et al*. 2007). This is supported by the strong positive correlation between $\delta^{13}C$ and $\delta^{15}N$ values ($r^2 = 0.767$, $p < 0.001$) seen in the Quanterness sheep (excluding the three cases thought to be medieval). Extending this analysis to include the sheep from HPWN and other Neolithic and Bronze Age sites on Orkney (Jones and Mulville 2016) reduces the strength of correlation ($r^2 = 0.609$, $p < 0.001$) but only because of the greater scatter at the low end of the scale for both elements (Figure 4). It is worth noting that, while the sheep/goat data presented by Jones and Mulville (2016: table 2) do not include any definite examples of seaweed consumption (average -20.8 ± 0.6‰, maximum -19.7‰, n = 26), three animals do have values above -20‰. Moreover, there is a slight but significant positive correlation between $\delta^{13}C$ and $\delta^{15}N$ values ($r^2 = 0.127$, $p = 0.045$), which may plausibly reflect some marine influence (cf. Richards and Hedges 1999). As Jones and Mulville (2012: 670; see also Jones *et al.* 2012) note, it is possible that this is the result of foreshore grazing on terrestrial plants enriched in ^{13}C and ^{15}N due to salinity effects (Heaton 1987; Britton *et al.* 2008), rather than the consumption of seaweed. However, this cannot account for the more elevated values seen in the young animals from Quanterness and HPWN. The absence of comparably elevated $\delta^{13}C$ values in the larger number of samples analysed by Jones and Mulville can be explained by their decision to focus only on mature animals, to avoid complications introduced by nursing effects (2012: 668). While entirely understandable, this creates ambiguity in the interpretation of the adult values, and could mask periods of significant consumption of marine resources.

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

Orcadian Neolithic and Bronze Age cattle, by contrast, show no correlation between $\delta^{13}C$ and $\delta^{15}N$ values ($r^2 = 0.059$, $p = 0.158$) (Figure 5). This is consistent with results from tooth enamel carbonate studies on cattle that have found no evidence for seaweed consumption (Balasse *et al.* 2006; Towers *et al.* 2016), despite their social and economic importance on Orkney from the Neolithic onwards. This may reflect the more adaptable gut physiology of sheep, in particular their tolerance of the high levels of arsenic found in seaweeds (Caumette et al. 2007; Feldman *et al.* 2000). However, this cannot be the entire explanation, since supplementing cattle fodder with seaweed is well attested historically (Hallson 1964; Makkar *et al.* 2016; Martin 1703). Perhaps the greater value of cattle – and hence greater investment in them – meant that the bulk of the winter hay and chaff from C_3 plants was reserved for them.

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

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

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

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

The proportion of seaweed in the diet of the animals at HPWN suggested by the enamel $\delta^{13}C$ values (45-70%) would be expected to result in bone collagen values for the newborn lambs of ca. -14.7‰ to -17.0‰. While we cannot assume similar animal management practices between the two sites, it can be noted that, while the observed values for lambs in the 0-3 month age class at Quanterness do retain a ‘marine influence’, they are lower than this, ranging from -16.9‰ to -19.9‰. But, following on from the above discussion, newborn lambs would be nursing on milk produced by ewes feeding on new grass. Because of the rapid growth seen in the skeletons at this age, their bone collagen $\delta^{13}C$ values would change relatively rapidly, so that after three months they might very well fall within the observed range. The few older lambs that have been measured show no influence of seaweed. It is surprising that both they and the adult animals show so little input into their bone collagen of the winters spent, by at least some animals, during the first and second years of life consuming significant amounts of seaweed, as indicated by the sequential enamel measurements on second and third molars from Point of Cott and HPWN. While we cannot guarantee that any of the same animals were measured in the enamel and the bone collagen studies, given that *all* 12 molars analysed at HPWN showed seasonal consumption of seaweed, we would expect to find more evidence of this in the collagen of older animals, though admittedly there are only two measurements on adult sheep currently available from the site (Schulting and Richards 2009). That it was not detected at Knap of Howar is not surprising, since the enamel results did not find any evidence for the practice there.

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

Given that only very young animals show a distinct 'marine' $\delta^{13}C$ signal, it is possible that foddering pregnant ewes with seaweed was in fact a last resort when terrestrial resources failed, so that young animals born when their mothers had been on this diet were more likely to die, and hence retain elevated $\delta^{13}C$ values in their bone collagen. This is reminiscent of a recent study of sequential human dentine isotope measurements from a Neolithic site on the small island of West Voe, Shetland, showing that those individuals with periodic high use of marine resources were more likely to die young (Montgomery *et al.* 2013). In both cases the burial assemblage is intrinsically biased by differential survivorship – the classic ‘osteological paradox’ (Wood *et al.* 1992).

4.2 Implications for Neolithic human diet

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

Another finding to emerge from this study is that the use of direct radiocarbon dating of at least a sample of faunal remains is essential in those cases where the contemporaneity of the faunal assemblage cannot be securely assigned to a phase on archaeological/stratigraphic grounds. This is highlighted here by the fact that only three of the nine determinations returned results coeval with the use of the chambered tomb for burial in the Late Neolithic. Despite the presence of intrusive fauna, it is interesting to note that the early dates include one of the three pigs represented in the study. Pigs are relatively rare in Orcadian Neolithic faunal assemblages, and this can be explained by the limited availability of natural habitat suited to their foraging preferences (i.e., woodland). Hence, they would likely need to be supplied with food at least some of which would be suitable for humans, and would thus be in competition (McCormick and Buckland 2003: 91; Schulting 2013). A small number of pigs may have been fed on domestic refuse and crop waste. Pigs can also be fed marine foods (seaweed, shellfish, fish), but, surprisingly, there is no isotopic evidence for this in Orcadian prehistory. It is not until the Iron Age that we see convincing evidence for this practice, not in Orkney, but in the Western Isles (Jones and Mulville 2016: figure 13).

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

5. Conclusions

The faunal $\delta^{13}C$ and $\delta^{15}N$ data from Quanterness provide further evidence for the consumption of seaweeds, probably by pregnant ewes, on Orkney from the late fourth millennium BC, with additional cases in both the early and late third millennium, extending the temporal range of this practice into the Chalcolithic. However, the extent to which this was part of an ongoing, intentional management strategy remains unclear. An alternative scenario is that the use of seaweed was a fallback strategy in years where insufficient terrestrial grasses were available to last the winter. Only a very minimal increase in $\delta^{13}C$ values can be found in the bone collagen of older lambs and adult animals, so that little impact on human diets would be expected, consistent with what has been observed in the previously published human results from Quanterness (Schulting et al. 2010).

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

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Figures and Tables

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

Figure 2. Plot of δ^{13}C and δ^{15}N results from Quanterness

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

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

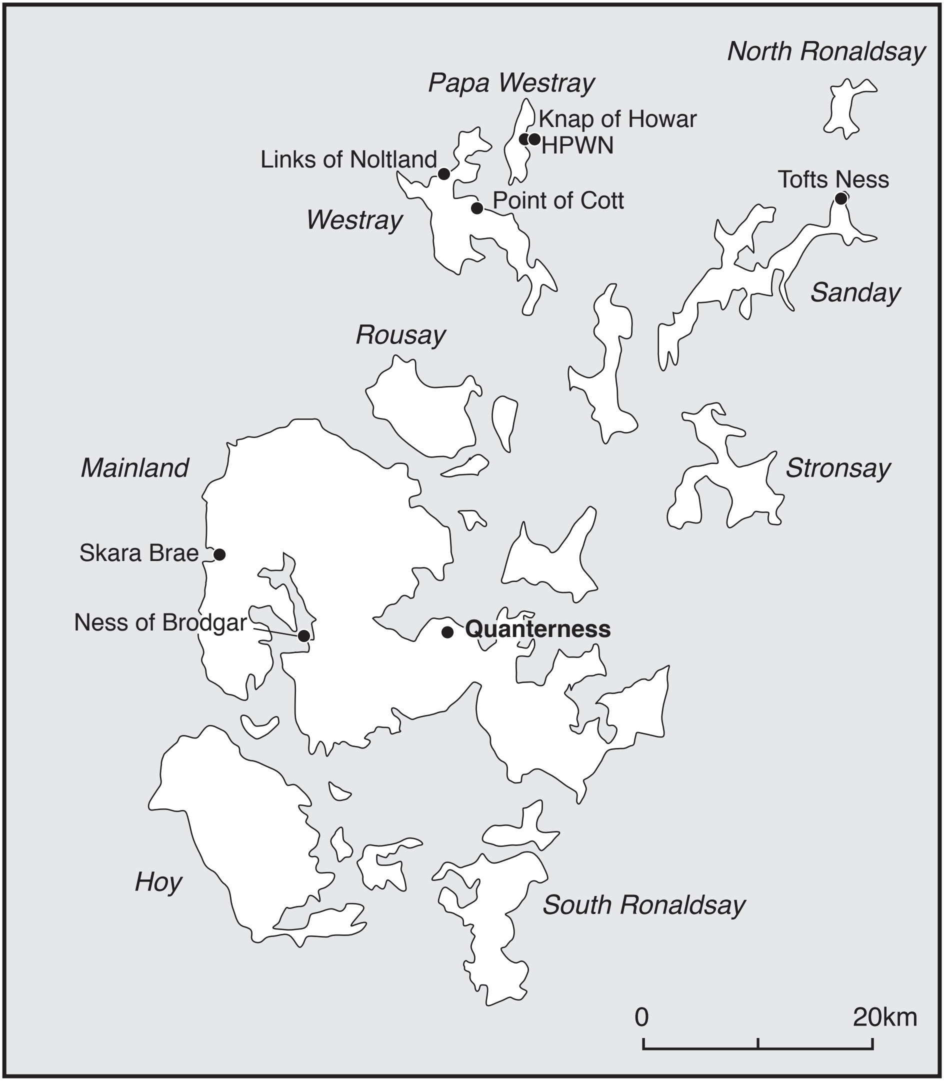
Figure 5. Plot of bone collagen δ^{13}C and δ^{15}N measurements on humans and fauna from Neolithic and Bronze Age Orkney (data: this paper; Jones and Mulville 2016; Schulting *et al*. 2010; Schulting and Richards 2009).

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

Table 1. Quanterness fauna sample details and results of δ^{13}C and δ^{15}N analysis.

Table 2. Summary statistics for Quanterness fauna δ^{13}C and δ^{15}N results.

Table 3. Results of ^{14}C dating. Mixed marine-terrestrial curves are used for the three juvenile sheep with significantly enriched ^{13}C (Reimer *et al.* 2013).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Knap of Howar
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Links of Noltland
Tofts Ness
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Westray
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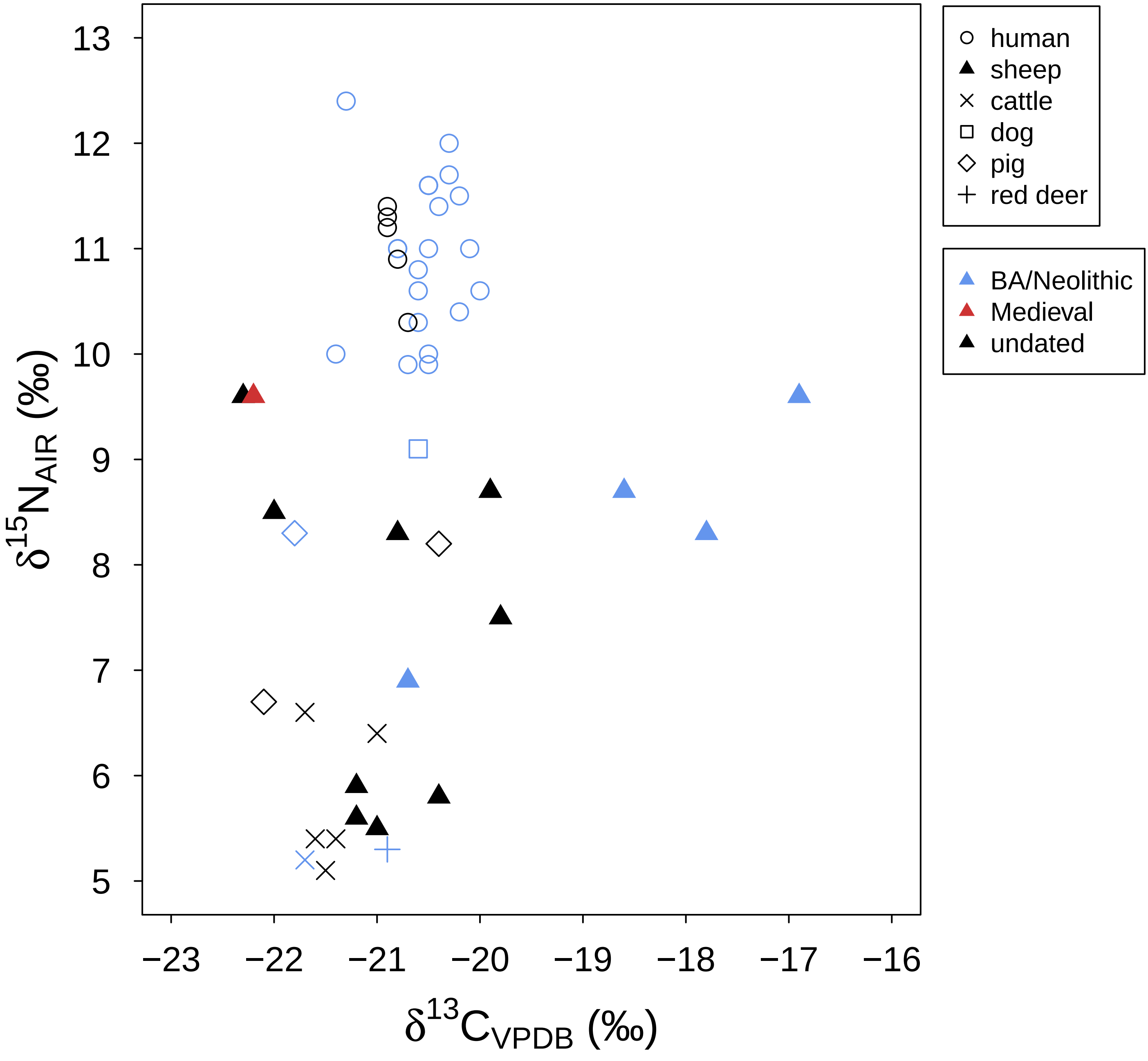
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$\delta^{15}N_{AIR}$ (‰)
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□ dog
◇ pig
+ red deer
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▲ Medieval
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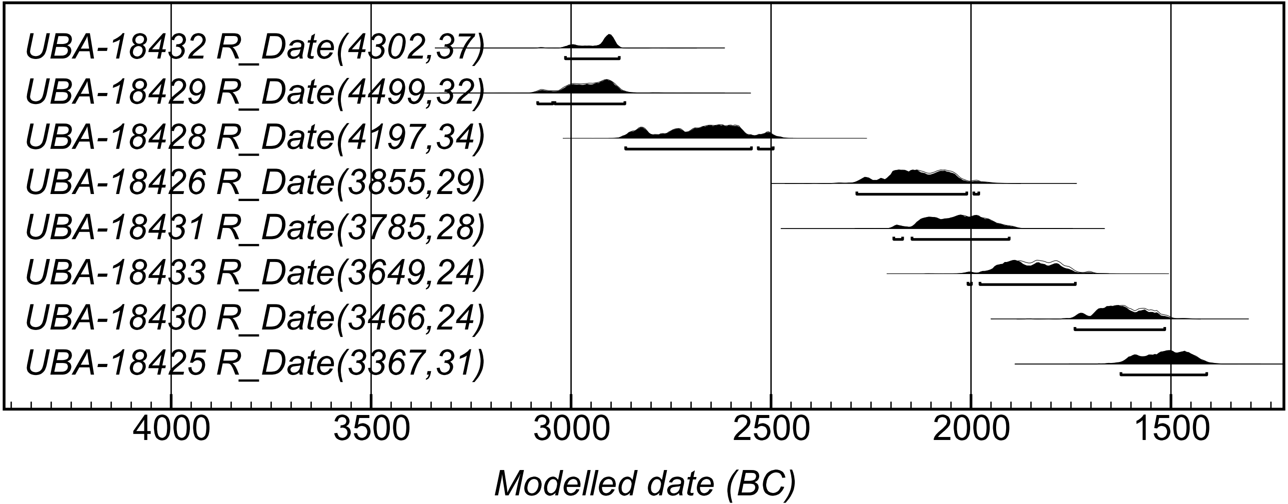
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UBA-18431 R_Date(3785,28)
UBA-18433 R_Date(3649,24)
UBA-18430 R_Date(3466,24)
UBA-18425 R_Date(3367,31)
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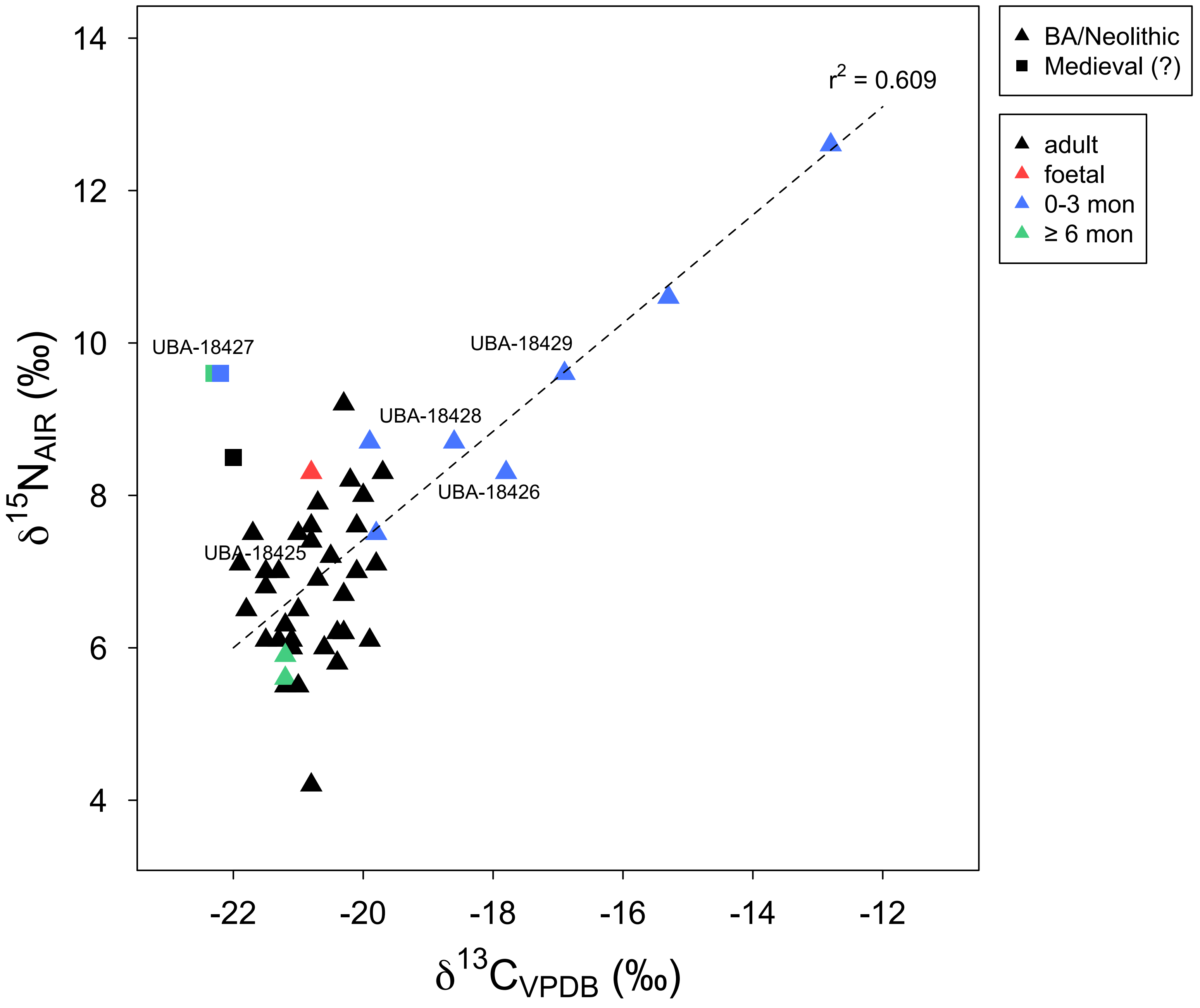
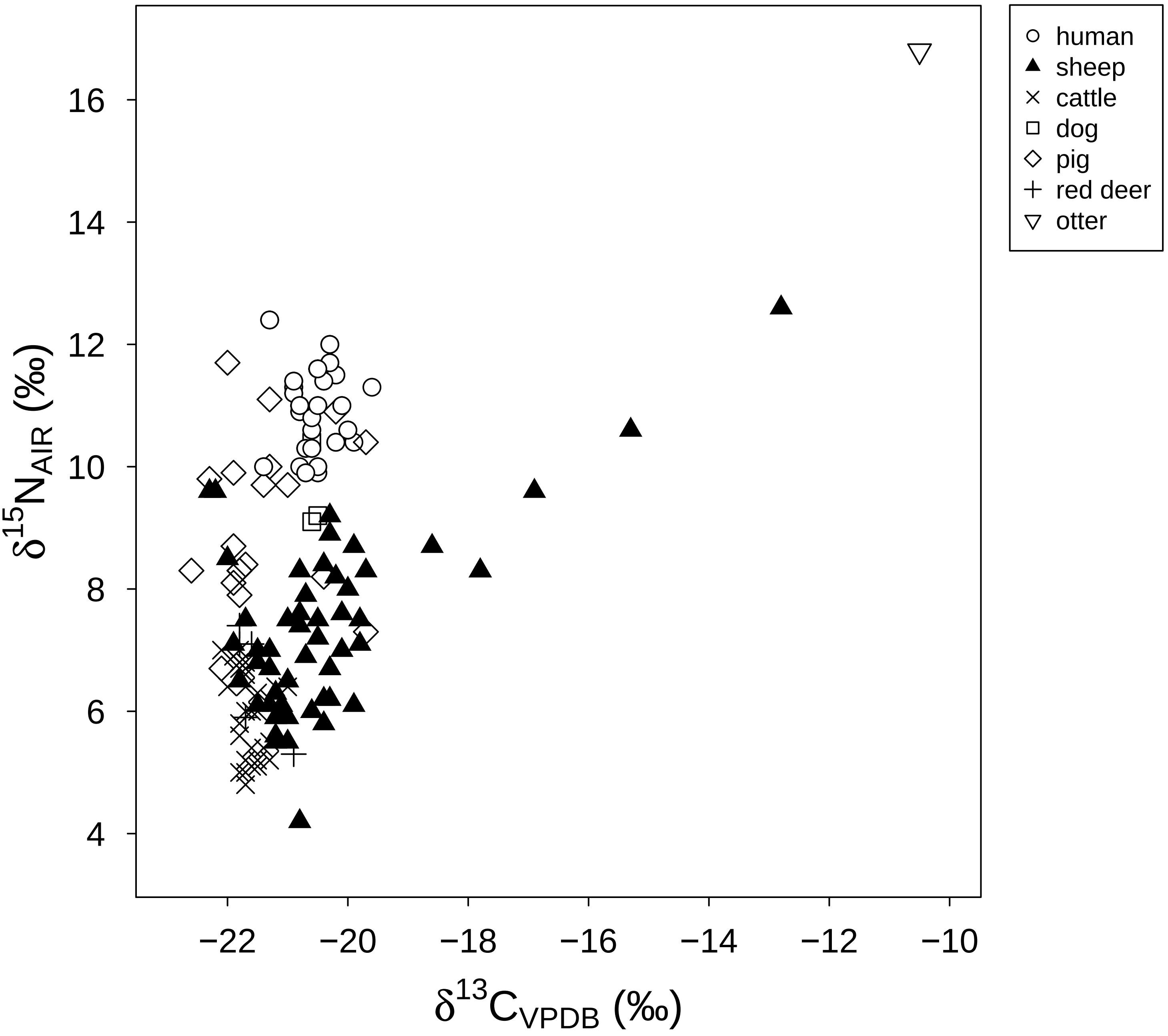
1500
Modelled date (BC)



BA/Neolithic
Medieval (?)
adult
foetal
0-3 mon
≥ 6 mon
r² = 0.609
UBA-18427
UBA-18429
UBA-18428
UBA-18426
UBA-18425
14
12
10
8
6
4
-22
-20
-18
-16
-14
-12
δ¹³C_VPDB (‰)
δ¹⁵N_AIR (‰)



16
14
12
10
8
6
4
−22
−20
−18
−16
−14
−12
−10
$\delta^{15}N_{AIR}$ (‰)
$\delta^{13}C_{VPDB}$ (‰)
○ human
▲ sheep
× cattle
□ dog
◇ pig
+ red deer
▽ otter

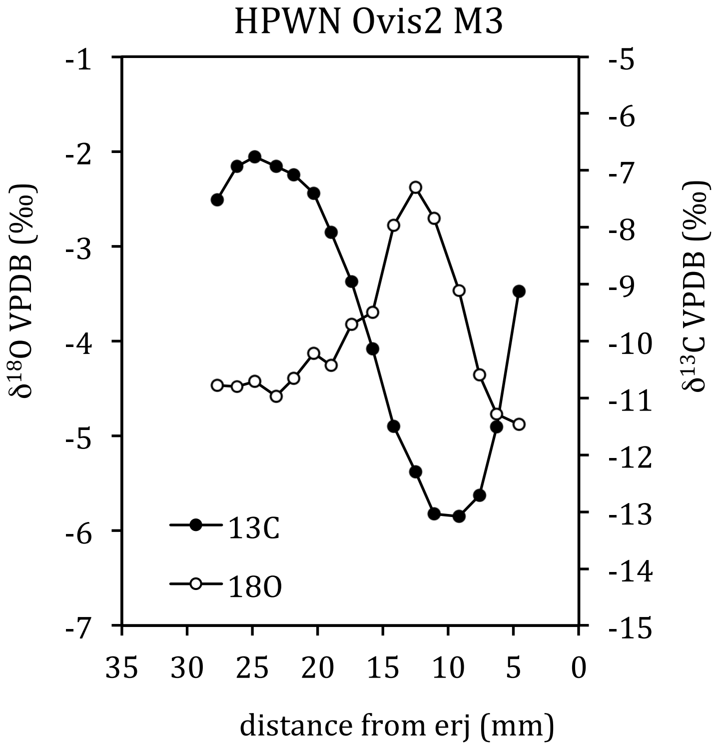


Figure 6a

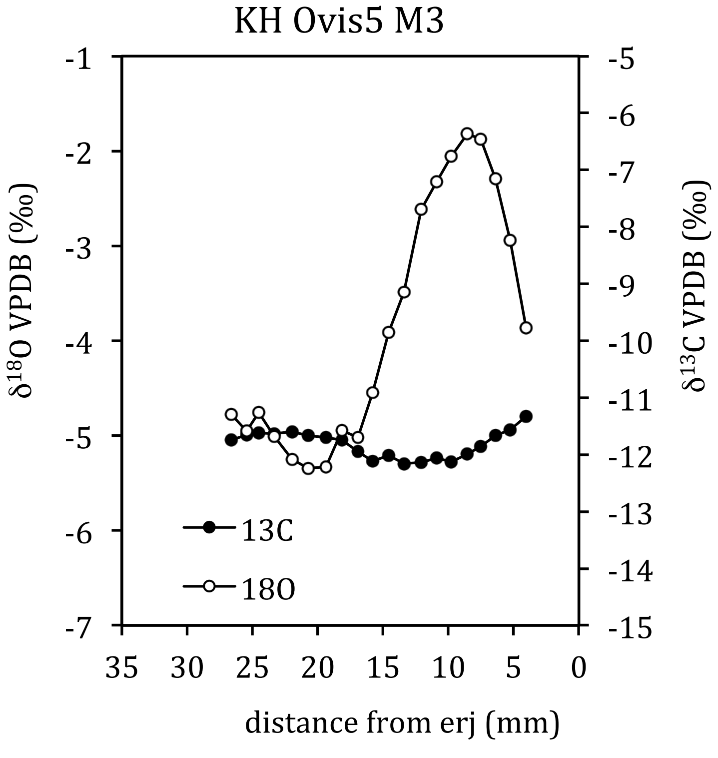


Figure 6b