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Strategic and sporadic marine consumption at the onset of the Neolithic: increasing temporal resolution in the isotope evidence

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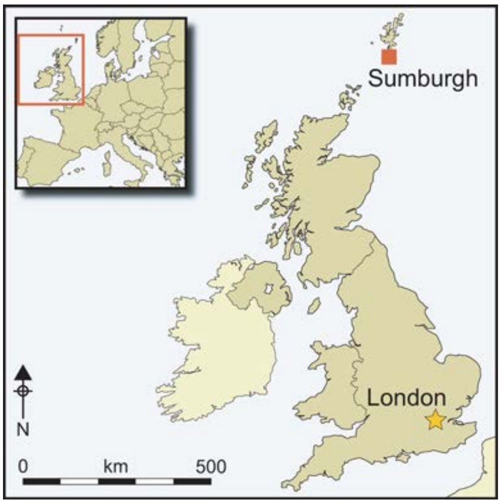

Stable isotope analysis has provided crucial new insights into dietary change at the Neolithic transition in north-west Europe, indicating an unexpectedly sudden and radical shift from marine to terrestrial resources in coastal and island locations. Investigations of early Neolithic skeletal material from Sumburgh on Shetland, at the far-flung margins of the Neolithic world, suggest that this general pattern may mask significant subtle detail. Analysis of juvenile dentine reveals the consumption of marine foods on an occasional basis. This suggests that marine foods may have been consumed as a crucial supplementary resource in times of famine, when the newly introduced cereal crops failed to cope with the demanding climate of Shetland. This isotopic evidence is consistent with the presence of marine food debris in contemporary middens. The occasional and contingent nature of marine food consumption underlines how, even on Shetland, the shift from marine to terrestrial diet was a key element in the Neolithic transition.

Keywords: Shetland, Mesolithic–Neolithic transition, marine consumption, stable isotopes, dentine, bone

Supplementary material, including Tables S1–5 and Figure S1, is provided at the end of this document.

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Introduction

Stable isotope analyses of Mesolithic and Neolithic human bone collagen from northern and western Europe have been reported to demonstrate a sharp shift away from the consumption of marine foods at the onset of the Neolithic (Tauber 1981; Richards *et al*. 2003). This has led to controversy over the apparent contradictions between the Neolithic archaeology and the isotope data, with part of the discussion being presented previously in *Antiquity* (Richards & Mellars 1998; Schulting & Richards 2002; Bailey & Milner 2003; Hedges 2004; Milner *et al*. 2004; Richards & Schulting 2006; Bonsall *et al.* 2009). Some coastal site middens contain thousands of marine ecofacts, suggesting that these resources must have played a significant part in the subsistence base, and the suggestion that this was not the case has also raised questions about why coastal dwellers would reject a readily available food resource in the early days of establishing agriculture, especially on marginal and remote islands. The previously published work has utilised adult human bulk bone collagen which provides an average of many years' diet and is thus a relatively blunt tool providing only blurred temporal focus (Hedges *et al.* 2007). In the research presented here we have used a new technique which utilises high-precision dentine increments, allowing us to increase temporal resolution and identify dietary patterns over very short periods of an individual's early life. Our findings hold significance not only for Neolithic Shetland, which has "remained something of an enigma" (Sheridan 2012: 6), but also for understanding how the first farmers in marginal regions across Atlantic Europe survived during periods of resource shortages and famine. The results also address the paradox between the mainly terrestrial dietary isotope ratios of humans and the continued presence of marine food remains at some Neolithic sites.

A marginal environment for early farmers

Our study uses material dating to the Mesolithic–Neolithic transition from the Shetland Islands: at 60° N, these are the most northern Scottish islands in the North Atlantic (Figure 1) and an ideal place to test the hypothesis that marine resources would be included in the north-west European diet during this period if conditions were difficult. Even accounting for the Holocene hypsithermal, the climate would have been marginal for agricultural purposes and expected to generate periods of crop failure and famine (Birnie *et al.* 1993). According to the 'dietary shift' model, marine resources are proposed to have been abandoned by choice at the Mesolithic–Neolithic transition. The best place to confirm this is a coastal, marginal

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environment where there is every reason to believe that such resources would be key to survival.

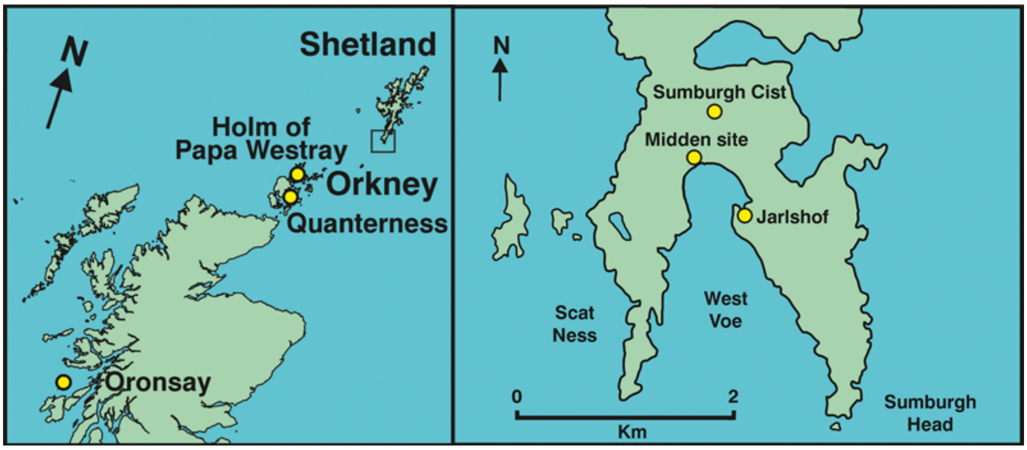


Figure 1. Map showing the Shetland and Orkney Islands in the North Atlantic and Oronsay on the west coast of Scotland (left); and the locations of Sumburgh, West Voe and Jarlshof on Shetland (right).

The disarticulated remains of a minimum of 11 adults and 9 juveniles and infants (Walsh *et al.* 2012) were recovered from a stone-lined, sub-rectangular pit, a non-megalithic funerary monument of a type not previously suspected, that was uncovered during the 1977 construction works at Sumburgh Airport, at the southern tip of the archipelago (Hedges & Parry 1980) (Figure 2). They are the only skeletal remains of the Early Neolithic inhabitants to be recovered from these islands. The importance of this area to the colonisation of the archipelago has been further demonstrated by a Late Mesolithic-Early Neolithic sequence of middens exposed by coastal erosion at West Voe, some 400m to the south (Melton & Nicholson 2004, 2007; Melton 2009), and by recent investigations at the internationally renowned site of Jarlshof, on the opposite side of the voe (Dockrill & Bond 2009) (Figure 1). The human remains have been dated to between 3510 and 2660 BC (14 radiocarbon dates, calibrated taking into account a marine dietary component; details in Table S1). The two superimposed middens at West Voe are separated by a layer of sand and have been dated to *c.* 4300–3250 BC, the lower midden spanning the Mesolithic–Neolithic transition and the upper, which has provided dates of *c.* 3500–3250 BC, overlapping with the human remains found at Sumburgh. Mussels (*Mytilus edulis*), seals, seabirds and a few small fish were found in the uppermost layers of the lower midden together with sheep and cattle which predate the

Sumburgh humans. The upper midden was composed entirely of cockles (*Cerastoderma edule*), many of which were shattered and discoloured from being heated, with continuing evidence for sheep and cattle in associated layers and contemporary with the human remains (Melton 2008, 2009).

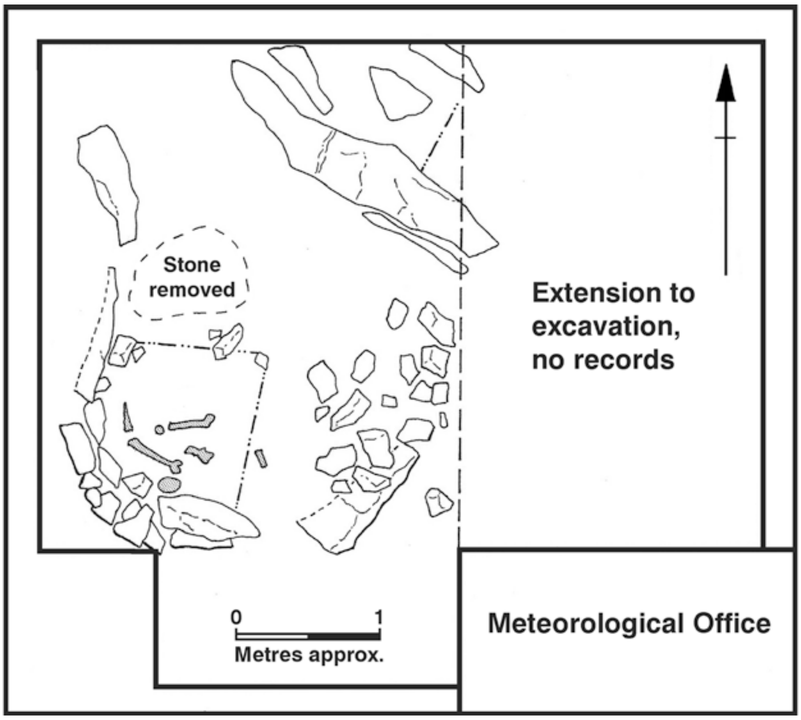


Figure 2. Plan of the cist at Sumburgh interpreted by N.D. Melton and S. Walsh from excavation photographs taken by G. Parry and archived at the RCAHMS. Human bones are identified by stippling.

Together, they provide direct evidence for subsistence practices adopted by the earliest farmers, with the exploitation of marine resources (molluscs, fish, seals and seabirds) apparently continuing alongside the adoption of agriculture, represented by finds of cattle (confirmed by proteomics analysis, M. Buckley *pers. comm.*) and sheep bones. The recent investigations at Jarlshof have provided radiocarbon dates of 3770–3610 and 3640–3380 BC (both 95% probability; SUERC-15163 & 15123) from an oyster shell and a charred grain of six-row barley respectively, recovered from the earliest archaeological horizon. The dates indicate that this layer is equivalent to some of the earliest deposits in the West Voe midden sequence. The investment of labour to produce fertile soils, initially by a build-up of ash-rich midden material followed by organic additives, permits intensive arable production within small managed plots. These soils provide an inherited resource that can build in depth through time and be passed on to future generations; they also form a catalyst for sedentary living. The crop six-row barley has an added advantage as a commodity whose storable surplus in ‘good years’ might be used in times of famine. Resilience and sustainability demonstrated by the longevity of settlements could only be achieved at such times of yield shortage (‘bad years’) by the combined use of other resources within the mixed economy (Dockrill & Bond 2009: 43–45). The archaeological evidence thus points to the existence of a mixed agricultural economy, supplemented by the exploitation of marine resources, at the time of the Sumburgh burials. The burials cut into a 0.5m thick layer of storm sands which were deposited *c*. 3500 cal BC. These sands separate the two middens at West Voe (Gillmore & Melton 2011) and suggest that much of the local area had been inundated by sand just prior to the commencement of the interments at Sumburgh, increasing its agricultural marginality and necessitating the creation of anthrosols capable of cereal production.

Carbon and nitrogen isotope data

One of the most widespread uses of δ^{13}C and δ^{15}N values (the ratios of ^{13}C/^{12}C and ^{15}N/^{14}N in a sample, relative to international standards) in the context of palaeodietary studies is to document the consumption levels of marine resources in prehistory. Marine food webs are significantly enriched in ^{13}C compared to those terrestrial resources which have a C_3 photosynthetic pathway, while the effects of marine environments and trophic levels mean that consumers of marine resources will also show higher δ^{15}N values (Lee-Thorp 2008). The expectation for individuals with significant levels of such resources in their diet relative to those with purely terrestrial C_3 diets is that both δ^{13}C and δ^{15}N values from their collagen extracts will be higher. In this study, no consideration of C_4 terrestrial diets is required since such plants were not present in prehistoric Britain.

The problem and the solution

Existing isotope data suggest the abandonment of marine food consumption at the Mesolithic–Neolithic transition. Not only does the archaeological evidence sometimes appear to refute the isotope data, but it seems counterintuitive that the early farmers living at isolated and marginal coastal locations would completely abandon an easily obtained resource. A problem which has been difficult to address is that bulk bone collagen, which is the material usually investigated for the isotope analyses, reflects a weighted averaged diet over a long period of an individual's life (Hedges *et al.* 2007). This means that short periods of unusual consumption, such as might occur when marginal environments do not yield sufficient terrestrial resources (e.g. sporadic and unpredictable crop failure), will not be visible in the target tissue. For this study we have used three distinct skeletal collagen fractions with progressively finer temporal resolution: (1) bulk bone; (2) bulk dentine; and (3) small (*c.* 1mm/20mg) incremental dentine samples. The collagen in primary dentine, unlike bone, does not remodel once mineralisation is complete, and the age at which human teeth begin to form and the duration of their growth has been well established (Hillson 2005; AlQahtani *et al.* 2010). New techniques for targeting small incremental dentine samples which have formed over periods of less than a year, as opposed to the larger increments covering several years (Fuller *et al.* 2003), allow a temporally focused study of an individual's diet in which short periods of marine consumption may be visible (Beaumont *et al.* 2013).

Samples analysed

Collagen was extracted from: (1) 12 bulk bone samples; (2) bulk samples of the root dentine of 17 permanent second molars; and (3) incremental dentine samples processed from a further eight teeth. Methods are described in Beaumont *et al.* (2013; Method 2 for incremental sampling) and samples are detailed in Table S2. Up to 21 incremental transverse samples from root apex to enamel-dentine junction were taken from each tooth in the third group. These increments span periods of formation, depending on the tooth involved, from just before birth up to 15 years. These three fractions therefore represent: (1) lifetime averaged diet; (2) childhood averaged diet; and (3) serial data for short periods of less than a year throughout childhood.

The composition of the primary dentine used in this study is, like enamel, determined largely at the time of formation (Rowles 1967; Veis 1989). Nevertheless, the cells of dentine, the odontoblasts, remain active, and formation of new, secondary dentine continues throughout life, in layers lining the pulp cavity (van Rensburg 1987; Hillson 2005). The presence of secondary dentine is used as an ageing technique and is rarely found in individuals below 30 years of age (Gustafson 1950). Further deposition of dentine mineral (as opposed to collagen) within the dentinal tubules may occur in the fourth decade of life, starting from the root tip and progressing at a relatively constant rate (Nanci 2003; Hillson 2005). Any change to dentine composition over time is, therefore, chiefly of an additive nature and will be negligible in individuals under the age of 30, such as those in this study (Table S2). As an extra precaution, all circumpulpal dentine was removed by reaming prior to demineralisation (Beaumont *et al.* 2013). Quality indicators for the processed samples are provided in Tables S3, S4 and S5 and all collagen, both from bone and dentine, fits well into the accepted ranges for atomic C:N ratios and percentages of carbon and nitrogen present (van Klinken 1999). The samples are, therefore, considered to be free of post-mortem contamination.

The disarticulated and commingled nature of the burial deposit means that it is not possible to directly associate bone samples with teeth. Whilst it is a possibility that the bone samples come from a group of individuals with dietary histories different from a second group represented only by the teeth samples, it is an exceptionally unlikely one: the osteological analysis of the material concluded that there were 11 adults and 9 juveniles or infants present, totalling 20 individuals (Walsh *et al.* 2012), whilst the sampled dental assemblage of 25 teeth represents a minimum number of 13 individuals (7 adults and 6 juveniles) (Table S2). Two of the juvenile bulk dentine samples (SUMB-5 and SUMB-11: upper and lower right second molars) may have come from the same individual, based on tooth development and similarity of isotope ratio data.

Mesolithic–Early Neolithic bone collagen data for terrestrial animals, seals and seabirds from West Voe and Sumburgh have also been obtained, together with modern *Cerastoderma edule* (cockle) flesh. The midden material suggests that cockles were available and used during the Neolithic, but the flesh is not preserved in the archaeological contexts. The modern proxies were collected in order to provide an estimate of their place in the food web, although the data obtained have not been adjusted for the fossil fuel effect (see online supplementary information).

Results: bone collagen and bulk dentine collagen

Figure 3 (using data from Tables S3 and S4) plots the Sumburgh bone and bulk dentine data separately (sample types (1) and (2)) with comparative Mesolithic and Neolithic human data published for other Scottish islands (Orkney Islands and Oronsay, see Figure 1). Also plotted are archaeological animal bone data from the West Voe middens and Sumburgh, together with the modern cockle flesh (see Table S4). The Mesolithic Oronsay humans are high-level marine resource consumers (plotting with the Neolithic marine-consuming animals), whilst the Neolithic Orkney Islands individuals are considered to have a mainly terrestrial diet

(Schulting & Richards 2009; Schulting *et al.* 2010). The highest δ^{13}C value for the comparative Neolithic data sets (–19.1‰) is used as a *conservative* limit for a largely terrestrial diet. The diet in that case was interpreted as mainly terrestrial, although a small percentage of marine resources may have been present and this is one of many locations in Europe where the evidence seems to suggest a low level of such consumption which is not easily identified from the bulk stable isotope data (Lubell *et al.* 1994; Fischer *et al.* 2007; Eriksson *et al.* 2008; Bonsall *et al.* 2009; Smits *et al.* 2010). Those individuals with carbon isotope ratios more enriched in ^{13}C than this limit are seen to the right of the middle vertical line and it is these that are indicative of a marine component in the diet. Only one of the bone collagen samples falls to the right of the line together with 11 of the 25 bulk dentine data points which are enriched in both ^{13}C and ^{15}N. There is no correlation between the Sumburgh radiocarbon dates and the level of marine consumption (Figure 4) and thus no suggestion that the earliest Neolithic humans from this group relied more heavily on marine resources than those living there later in the period.

δ^{13}C values are affected by local environmental conditions as well as dietary considerations. For this reason, comparisons are best made with data sets from the same region and this is why the Orkney Neolithic data have been shown here. End-members for terrestrial and marine diets have been empirically estimated at –21.0‰ and –12.4‰ respectively and between these two extremes the upper boundary for terrestrial diets, the lighter blue line in Figure 3, as –19.1‰. Terrestrial diets in the region, therefore, are conservatively deemed to range between the boundary value of –19.1 ‰ and the terrestrial end-member (–21.0‰; the green line in Figure 3), discussed in the online supplementary material for the calibration of the radiocarbon dates. This upper boundary is used for illustration based on the interpretation of the geographically closest available data set for the time and place under discussion. It would not necessarily reflect a purely terrestrial diet in north-west Europe, however, but more probably a low level of marine resource consumption at some time in an individual's life. A more likely boundary for a purely terrestrial diet in this region is –20.0‰ (Bonsall *et al.* 2009). If that were used in this chart, the distinctions being highlighted would only be reinforced. By using the more conservative boundary value of –19.1‰, Figure 3 shows the very clear difference between the analyses of bone collagen (an averaged lifetime dietary input) and those of dentine (childhood dietary input) even where a low level of marine consumption may be present.

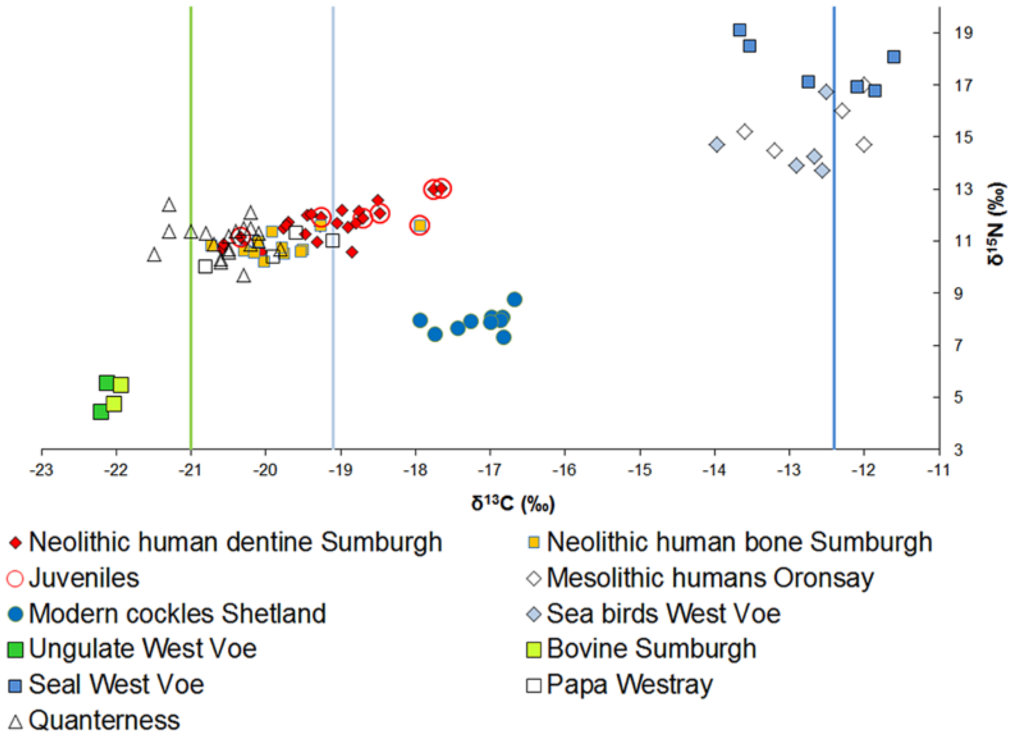


Figure 3. Carbon and nitrogen stable isotope ratios for Sumburgh bone and bulk dentine, with comparative Scottish island Neolithic and Mesolithic data. Samples from Middle to Late Neolithic Quanterness (Schulting et al. *2010) and Holm of Papa Westray (Schulting & Richards 2009) are all human bone; both sites are in Orkney. Mesolithic humans are from Oronsay (Richards & Mellars 1998). The modern cockle muscle samples have not been adjusted for the Suess effect (see online supplementary information). The light blue vertical line represents the limit of the highest $\delta^{13}C$ value for the Orkney Neolithic material, a conservative estimate for the limit at which the diet might be considered mainly terrestrial. The dark blue and dark green lines are the estimates for 100 per cent marine and terrestrial diets respectively, as used for calibrating the radiocarbon dates (Table S1).*

Individuals who were juveniles at the time of death are circled (Figure 3), with the bone collagen sample that is highlighted as a marine consumer being from a five- to six-year-old child (Walsh *et al.* 2012). The bone collagen values represent a weighted lifetime dietary average (Hedges *et al.* 2007), whilst the dentine reflects only childhood. Thus the bulk dentine samples and the juvenile bone (which represents no more than seven years of life) appear to indicate low level marine resource consumption during childhood which is not visible in the adult bone samples. Three of the $\delta^{13}C$ values are above –18.0‰, indicating a relatively higher level of marine food consumption: all are juveniles. Two are bulk dentine analyses of incompletely formed roots (SUMB-5 and SUMB-11; Figure 5) and are suspected to be from the same individual aged 11.5 to 12.5 years at death. The third is the bone of the

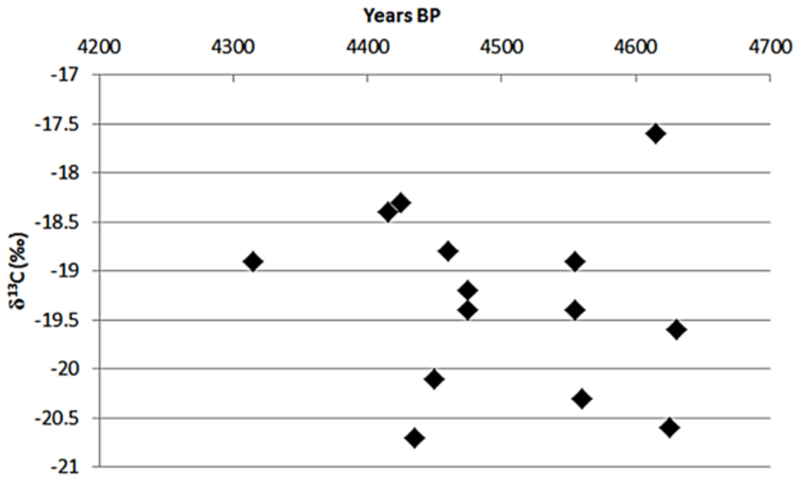


Figure 4. Carbon stable isotope ratios plotted against radiocarbon age BP for dated dentine samples (see Table S1 for dating details). There is no correlation between date and the higher $\delta^{13}C$ *values, suggesting that marine consumption patterns do not change over time during this period.*

five- to six-year-old child. In addition, the $\delta^{13}C$ values of enamel apatite which derive from the whole diet (i.e. not just protein consumption) in early childhood (Lee-Thorp *et al.* 1989) range from –16.7‰ to –14.0‰ (Keefe 2007). The difference between the isotope values obtained from dentine collagen and enamel apatite of each individual tooth ranges from -5.7‰ to –2.9‰. These differences indicate a dietary range from a fully terrestrial/C_3 based diet through to one with a substantial component of marine animal protein and thus concur with the conclusions drawn from collagen alone (Lee-Thorp *et al.* 1989; Froehle *et al.* 2010). Overall, this suggests that marine foods were a significant part of the diet of young children but were no longer detectable in completed tooth roots or adult bone samples. Did only children eat marine protein? Was childhood-only consumption no longer visible in adult bone collagen due to remodelling? Or were marine foods eaten by both adults and children for short periods of time, such as a period of crop failure, which would not be resolvable in adult bone due to slow bone turnover and lifelong averaging?

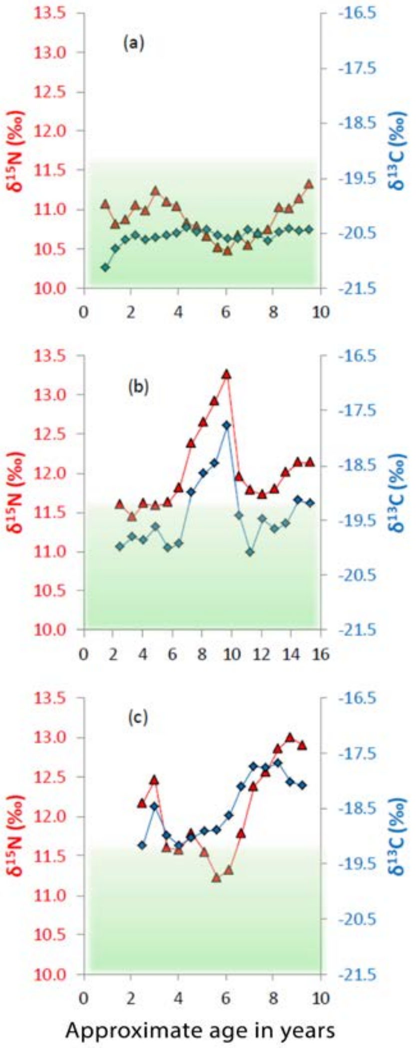
Results: incremental dentine samples

The age-constrained incremental dentine samples provide increased focus to resolve this issue. Figure 6 shows data from three of the eight teeth sampled in this way (the other five are shown in Figure S1). Only one of the eight teeth (SUMB-41) shows a relatively low variation in both $\delta^{13}C$ and $\delta^{15}N$ values that remain within the terrestrial diet range over the first 10 years of life (Figure 6a). For the other seven, the fluctuations have no consistent pattern of chronology or magnitude, although the data for carbon and nitrogen isotopes co-vary at most points and all indicate the likelihood of a period of marine consumption at some time during childhood. The most extreme of the fluctuations is shown for SUMB-42, an individual who survived to adulthood, but between the ages of 7 and 10 appears to have been a high-level marine food consumer (Figure 6b).

Figure 5. Two of the teeth sampled in this study: (a) SUMB-5 is from a juvenile, 11.5 to 12.5 years of age, and was incompletely formed at death. It has paper-thin root edges; (b) SUMB-12 has completely formed roots, one of which is broken, and is estimated from tooth wear to belong to an adult aged 25–35 years (Table S2).

For most of the individuals, the relationship between the δ^{13}C and δ^{15}N values indicates that these fluctuations do not relate to breastfeeding at a late age as a possible alternative famine strategy. In that case, the δ^{13}C values would be expected to be lower given that the introduction of foods other than breast milk to the diet during the weaning process appears to have a bigger impact on δ^{13}C values than on δ^{15}N values (Fuller *et al.* 2006). The correlation between δ^{15}N and δ^{13}C, together with the magnitude of the higher δ^{15}N values, also rules out physiological stress as the driver for most of the samples (Mekota *et al.* 2006). SUMB-44, between the ages of 10 and 16, does show a combination of relatively high δ^{15}N values with δ^{13}C values within the range expected for a terrestrial diet (Figure S1c). This could be explained by the consumption of breast milk at a late age, or freshwater aquatic resources.

However, exclusively freshwater fish are unlikely to have been available as there are no native species in the Shetland Islands: today only a few species are established in the lochs and burns of Shetland, and all of them have a salinity tolerance or a marine phase and are thus unlikely to provide the required terrestrial δ^{13}C values (Johnston 1999: 116–17; Robson *et al.* 2012). A further interpretation for SUMB-44 is that the high δ^{15}N values record a period of nutritional or physiological stress (Mekota *et al.* 2006).



Three of these incrementally sampled teeth may indicate that periods of marine consumption equate with crises which have led to early mortality (SUMB-40, 8.8–9.5 years, Figure S1b; SUMB-43, 11.5–12.5 years, Figure 6c; SUMB-46, 6.5–7 years, Figure S1e). These teeth were incompletely formed at death as is also the case for SUMB-5 (Figure 5). Their three profiles show high δ^{15}N and δ^{13}C values at the end of their arrested sequence. In accordance with the bulk root dentine for SUMB-5 and SUMB-11, which was also still forming at death and for which very similar values were obtained, the data suggest that marine foods were an important part of the diet at the end of their lives.

Figure 6. Carbon and nitrogen stable isotope ratios of the incremental dentine samples from a) SUMB-41; b) SUMB-42; and c) SUMB-43. The shaded green area at the bottom of each chart represents a mainly terrestrial diet (see supplementary discussion). (a) First molar, age at death 17–25 years, no significant marine component to the diet indicated; (b) second molar, age at death 25–35 years, high level of marine component to the diet indicated at around age 9; (c) second molar, age at death 11.5–12.5 years, high level of marine component to the diet at time of death. Charts for the other five incrementally sampled teeth are available in the online supplementary information.

Conclusions

Sporadic dietary shifts from terrestrial to marine protein consumption are not visible in adult bone collagen data. That is one reason why there may be an apparent discrepancy between the isotope data for dietary change at the Mesolithic–Neolithic transition and the archaeological evidence, particularly in the form of marine resource remains in middens. Bulk dentinesamples suggest a marine input in childhood, but it is the novel high-resolution dentine increments which show that this is extremely unlikely to be long-term, low-level or seasonal supplementation of a terrestrial diet with marine foods. Instead, it is consistent with short-term episodes of high-level consumption at different ages in different individuals. This strategic consumption may be a response to unpredictable environmental crises which led to a shortage of terrestrial foods and possibly, for some children, death. The excavation of the later Neolithic Mound 11 on the Tofts Ness peninsula of Sanday, Orkney, provides evidence of an economy where grain (six-row barley) was harvested early and heavy emphasis was placed on fishing and bird capture; this suggests a site where such periods of shortage occurred (Dockrill & Bond 2007: 38). Added to this is the question of the contemporary organisation of society and how this might correspond to the social access to the economic resource (Dockrill & Bond 2007: 381).

The isotope data thus support the continued consumption of marine resources such as seal and seabirds at Sumburgh, as indicated by the archaeological assemblage at this marginal, coastal site, but only as a short-term strategy. It also implies that even at the edge of the Neolithic world, where the establishment of agriculture was difficult and conditions adverse, requiring the use of midden material and organic additives to establish small managed plots for cereal production (Dockrill & Bond 2009), the Early Neolithic inhabitants of the Shetland Islands were attempting to maintain a terrestrial diet, resorting to marine foods only when necessity demanded. In other words, the ‘dietary shift’ model at this time holds up even in an environment where marine resources were key to survival. This is an important step forward for understanding the development of the Neolithic in north-west Europe. The increased temporal resolution obtained from incremental dentine sampling brings the lives of ancient people into sharper focus and enables diet in the last few months of life to be ascertained. Attention should now be directed to less marginal, mainstream sites in Britain, Scandinavia and other parts of Europe to investigate whether marine foods were also consumed sporadically in the earliest Neolithic in regions more favourable to agriculture.

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Supplementary material

Modern cockle carbon isotope ratios

The values provided from the modern cockle flesh for consideration as part of the possible available dietary resource have not been adjusted for the fossil fuel effect (Suess effect) (Long *et al.* 2005; Pfister *et al.* 2011). Reduced atmospheric CO_2 $\delta^{13}C$ values, primarily due to fossil fuel combustion since industrialisation, will have affected the modern samples when compared to the archaeological material. It is to be expected that the values for prehistoric cockle flesh would be higher than the modern. An estimate for this shift might be 1–2‰, although it is not possible to be precise. Such an adjustment would have no substantive effect on the conclusions in this paper.

Table S1. Radiocarbon dates of Sumburgh humans.

Sample code	Lab number	^{14}C age (yr BP)	1σ error	Marine diet %	Calibrated ages (95.4%) and major probabilities
SUMB-45	SUERC-37437	4315	30	24	2930 (95.4%) 2660BC
SUMB-46	SUERC-37441	4415	30	30	3090 (95.4%) 2860BC
SUMB-43	SUERC-37435	4425	30	31	3090 (95.4%) 2860BC
SUMB-41	SUERC-37433	4435	30	3	3340 (25.3%) 3210BC; 3190 (5.0%) 3150BC; 3140 (65.1%) 2910BC
SUMB-8	SUERC-14984	4450	40	10	3340 (21.9%) 3210BC; 3200 (5.2%) 3150BC; 3140 (68.3%) 2900BC
SUMB-40	SUERC-37432	4460	30	26	3120 (92.6%) 2880BC
SUMB-42	SUERC-37434	4475	30	19	3330 (16.2%) 3210BC; 3190 (3.2%) 3150BC; 3130 (75.9%) 2900BC
SUMB-44	SUERC-37436	4475	30	21	3330 (13.3%) 3210BC; 3190 (2.4%) 3150BC; 3130 (79.6%) 2900BC
SUMB-13	SUERC-14986	4555	40	19	3360 (94.5%) 3010BC
SUMB-14	SUERC-14987	4555	40	24	3360 (93.5%) 3000BC
SUMB-7	SUERC-14980	4560	40	8	3370 (93.2%) 3080BC
SUMB-11	SUERC-14985	4615	40	40	3360 (95.4%) 2960BC
SUMB-24	SUERC-15178	4625	35	5	3510 (25.7%) 3420BC; 3390 (42.4%) 3260BC; 3250 (27.3%) 3100BC

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SUMB-17	SUERC-14988	4630	40	16	3510 (15.7%) 3420BC; 3390 (79.7%) 3090BC

Notes to Table S1

Dating was undertaken at the Scottish Universities Environmental Research Centre (SUERC) in Glasgow, UK. All of the dated samples had δ^{13}C values higher than –21‰ (Table S3) and this was taken to be the terrestrial end member (0% marine diet) when calibrating the dates using an assumed marine component to the diet. Previous work has suggested that –20.9‰ is a suitable calibration value for the Neolithic diet in north-west Europe generally (Bonsall *et al.* 2009). The value for the marine end member used was –12.4‰ based on the average values for seal, seabird and cockle in equal proportions plus one trophic level. Percentage marine diet was estimated using a linear interpolation between the 100% terrestrial and 100% marine dietary end members. Linear equations were also derived using the heaviest and lightest end member values, giving an average deviation from the mean value of 11%. Therefore, the estimated percentage marine diet ±11% was used in the calibration. A ΔR value of 7±48 ^{14}C years was determined from recalculation of data in Ascough *et al.* (2007) to provide a weighted mean value ± standard error for predicted values. Using this ΔR value and the estimated percentage marine diets, the ^{14}C ages were calibrated using the OxCal 4.1 (Bronk Ramsey 2009) mixed curve (Marine09 [Reimer *et al.* 2009]).

Table S2. Teeth analysed, age at death and minimum number of individuals for each Sumburgh dentine sample.

Sample no.	Tooth	Root development	Minimum possible age at death (in years)	Estimated age at death (in years)
SUMB-39	LLE	apex closed	3–3.5	<9
SUMB-46	LRM1	Rt 3/4	6.5–7	6.5–7
SUMB-40	ULI1	complete	8.5–9.5	8.5–9.5
SUMB-4	ULM2	Rt 1/2	10.5–11.5	10.5–11.5
SUMB-5	URM2	Rt 3/4	11.5–12.5	11.5–12.5
SUMB-6	URM2	Rt 3/4	11.5–12.5	11.5–12.5
SUMB-11	LRM2	Rt 3/4	11.5–12.5	11.5–12.5
SUMB-43	LRM2	Rt 3/4	11.5–12.5	11.5–12.5

Table S2 continued.

Sample no.	Tooth	Root development	Minimum possible age at death (in years)	Estimated age at death (in years)
SUMB-2	ULM2	apex closed	14–15	17–25
SUMB-7	ULM2	apex closed	14–15	17–25
SUMB-16	ULM2	apex closed	14–15	17–25
SUMB-17	ULM2	apex closed	14–15	17–25
SUMB-8	URM2	apex closed	14–15	17–25
SUMB-24	URM2	apex closed	14–15	17–25
SUMB-41	URM1	apex closed	9–10	17–25
SUMB-45	LLM1	apex closed	9–10	17–25
SUMB-3	LLM2	apex closed	14–15	25–35
SUMB-12	LLM2	apex closed	14–15	25–35
SUMB-42	LLM2	apex closed	14–15	25–35
SUMB-44	LLM2	apex closed	14–15	25–35
SUMB-9	URM2	apex closed	14–15	25–35
SUMB-14	URM2	apex closed	14–15	25–35
SUMB-15	URM2	apex closed	14–15	25–35
SUMB-10	ULM2	apex closed	14–15	25–35
SUMB-13	ULM2	apex closed	14–15	25–35

Notes to Table S2

Tooth identification: the first letter (L or U) indicates upper (maxillary) or lower (mandibular); the second letter (L or R) indicates left or right; the third letter and associated number indicates the tooth (E = deciduous second molar; I1 = first incisor; M1 = first molar; M2 = second molar). The minimum possible age at death is based on tooth root development (AlQahtani *et al.* 2010) and the estimated age at death is based on tooth wear (Brothwell 1981; AlQahtani *et al.* 2010). The MNI (Minimum Number of Individuals), based on age and tooth type, totals 13. Based on the isotope analyses, it is likely that the majority of the samples are from separate individuals, although SUMB-5 and SUMB-11 may be from the same child.

Table S3. Carbon and nitrogen stable isotope data for the human bulk dentine and bone samples.

Sample no.	Age	Material	δ^{13}C(‰)	δ^{15}N(‰)	%C	%N	C:N
SUMB-2	adult	dentine	-19.0	12.2	40.6	15.0	3.3
SUMB-3	adult	dentine	-18.8	11.7	42.2	16.4	3.0
SUMB-4	juvenile	dentine	-19.3	11.9	42.3	15.2	3.2
SUMB-5	juvenile	dentine	-17.8	13.0	42.1	15.3	3.2
SUMB-6	juvenile	dentine	-18.5	12.6	42.2	14.8	3.3
SUMB-7	adult	dentine	-20.3	10.8	43.1	15.7	3.2
SUMB-8	adult	dentine	-20.1	10.6	41.5	14.8	3.3
SUMB-9	adult	dentine	-19.3	11.0	42.1	15.2	3.2
SUMB-10	adult	dentine	-19.3	11.6	42.7	15.1	3.3
SUMB-11	juvenile	dentine	-17.6	13.0	40.8	14.6	3.3
SUMB-12	adult	dentine	-19.8	11.5	42.1	15.2	3.2
SUMB-13	adult	dentine	-19.4	12.0	43.5	15.8	3.2
SUMB-14	adult	dentine	-18.8	10.6	41.9	15.3	3.2
SUMB-15	adult	dentine	-19.7	11.7	40.3	14.0	3.3
SUMB-16	adult	dentine	-18.8	12.1	41.5	15.0	3.2
SUMB-17	adult	dentine	-19.5	11.3	41.5	15.2	3.2
SUMB-24	adult	dentine	-20.6	10.7	44.1	17.5	2.9
SUMB-39[c]	juvenile	dentine	-20.3	11.2	42.0	15.2	3.2
SUMB-40[c]	juvenile	dentine	-18.9	11.5	42.0	15.3	3.2
SUMB-41[c]	adult	dentine	-20.6	10.9	42.0	15.3	3.2
SUMB-42[c]	adult	dentine	-19.4	12.0	42.1	15.3	3.2
SUMB-43[c]	juvenile	dentine	-18.5	12.1	42.0	15.9	3.1
SUMB-44[c]	adult	dentine	-19.7	11.6	42.4	15.3	3.1
SUMB-45[c]	adult	dentine	-19.0	11.7	42.0	15.3	3.2
SUMB-46[c]	juvenile	dentine	-18.7	11.9	42.1	15.4	3.2
SUMB-25	juvenile	bone: rib	-17.9	11.6	46.5	17.5	3.1
SUMB-26	adult	bone: pelvis	-19.8	10.6	46.6	15.8	3.5
SUMB-27	adult	bone: cranium	-20.1	11.0	34.6	12.1	3.4
SUMB-28	adult	bone: ulna	-20.7	10.8	39.8	14.0	3.3
SUMB-29	adult	bone: long bone fragment	-19.9	11.4	37.1	12.3	3.5
SUMB-30	adult	bone: patella	-20.3	10.6	38.5	13.1	3.4
SUMB-31	adult	bone: scapula	-20.0	10.2	35.7	12.5	3.3
SUMB-32	adult	bone: rib	-19.5	10.7	40.6	14.5	3.3
SUMB-33	adult	bone: ulna	-19.3	11.6	42.5	14.7	3.4

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SUMB-34	adult	bone: rib	-20.2	10.6	36.9	12.6	3.4
SUMB-35	adult	bone: rib	-19.5	10.6	40.7	13.9	3.4
SUMB-36	adult	bone: ilium	-19.8	10.8	41.6	15.0	3.2

Notes to Table S3

Ages and tooth information are provided in detail in Table S1 for the dentine samples. Samples were measured in duplicate and the data averaged. SUMB-39 to SUMB-46 (marked c) are the eight samples for which incremental dentine analyses were undertaken and the data in this table are a combined mean for the increments (Table S5).

Table S4. Carbon and nitrogen stable isotope data for the animal samples.

The cow-sized ungulate, seal and shag (a type of cormorant) samples are all from the Late Mesolithic and Early Neolithic middens at West Voe. The cow samples are from the Sumburgh cist. The cockle muscle samples are all modern and were collected from Firths Voe, in the north of Mainland Shetland.

Sample no.	Species	Material	δ^{13}C(‰)	δ^{15}N(‰)	%C	%N	C:N
Sumb-19	cow	bone	-22.0	4.8	41.1	14.4	3.3
Sumb-22	cow	bone	-21.9	5.5	38.3	13.2	3.4
Wevo-1	ungulate	bone	-22.1	5.6	41.2	14.6	3.3
Wevo-2	ungulate	bone	-22.2	4.5	41.0	14.1	3.3
Wevo-3	seal	bone	-11.9	16.8	42.4	16.5	3.0
Wevo-4	seal	bone	-12.1	16.9	42.2	16.8	2.9
Wevo-5	seal	bone	-11.6	18.1	42.0	16.2	3.0
Wevo-6	seal	bone	-12.8	17.1	42.4	16.4	3.0
Wevo-7	seal	bone	-13.7	19.1	39.9	15.1	3.1
Wevo-8	seal	bone	-13.5	18.5	40.5	15.3	3.1
WV04 039a	bird: shag	bone	-12.5	16.7	42.8	16.7	3.3
WV04 057a	bird: shag	bone	-14.0	14.7	42.6	14.7	3.4
WV04 075a	bird: shag	bone	-12.6	13.7	43.0	14.7	3.4
WV04 076a	bird: shag	bone	-12.7	14.3	42.1	14.0	3.5
WV04 079a	bird: shag	bone	-12.9	13.9	42.4	14.3	3.5
SC1a	cockle	muscle	-17.0	8.1	44.7	12.9	4.2

SC2a	cockle	muscle	-16.8	8.1	45.7	13.9	3.8
SC3a	cockle	muscle	-16.9	8.0	46.1	14.2	3.8
SC4a	cockle	muscle	-17.4	7.7	45.9	7.7	3.9
SC5a	cockle	muscle	-17.9	8.0	44.7	8.0	4.8
SC6a	cockle	muscle	-17.0	7.9	45.5	13.9	3.8
SC7a	cockle	muscle	-16.8	7.3	44.0	12.3	4.2
SC8a	cockle	muscle	-16.7	8.8	44.7	8.8	4.1
SC9a	cockle	muscle	-17.3	8.0	46.6	8.0	4.0
SC10a	cockle	muscle	-17.7	7.5	45.1	7.5	4.4

Supplementary Table 5. Carbon and nitrogen stable isotope data for the incremental dentine samples.

The averages for each tooth are shown in bold and these are the data shown in Table S3. Each of the incremental samples was analysed in duplicate and averaged. The approximate age in years is based on the known incremental growth phases of the teeth analysed (Beaumont *et al.* 2013).

Sample no	**$\delta^{13}C$(‰)**	**$\delta^{15}N$(‰)**	**%C**	**%N**	**C:N**	**Approximate age in years**
SUMB 39 E 1	-20.9	10.9	45.9	16.4	3.3	-0.30
SUMB 39 E 2	-20.1	11.6	45.4	16.1	3.3	0.00
SUMB 39 E 3	-20.6	10.8	46.9	16.8	3.3	0.35
SUMB 39 E 4	-20.5	11.0	45.1	16.1	3.3	0.70
SUMB 39 E 5	-20.8	10.9	45.8	16.3	3.3	1.05
SUMB 39 E 6	-19.8	11.7	46.1	16.4	3.3	1.40
SUMB 39 E 7	-20.2	11.7	45.5	16.3	3.3	1.75
SUMB 39 E 8	-20.0	11.6	45.4	16.4	3.2	2.10
SUMB 39 E 9	-20.2	11.0	45.4	16.1	3.3	2.45
SUMB 39 E 10	-20.3	10.7	46.3	16.4	3.3	2.80
SUMB 39 E 11	-20.4	10.8	45.5	15.9	3.3	3.15
SUMB 39 E mean	-20.3	11.2	45.8	16.3	3.3	
SUMB 40 U1 1	-20.2	10.7	43.7	15.8	3.2	0.50
SUMB 40 U1 2	-19.7	10.8	45.5	16.4	3.2	0.93
SUMB 40 U1 3	-19.2	11.4	45.1	16.3	3.2	1.36
SUMB 40 U1 4	-18.9	11.8	45.4	16.4	3.2	1.79

SUMB 40 U1 5	-18.6	12.0	45.3	16.4	3.2	2.22
SUMB 40 U1 6	-18.5	12.1	41.8	15.1	3.2	2.65
SUMB 40 U1 7	-18.6	12.0	49.0	17.7	3.2	3.08
SUMB 40 U1 8	-18.4	12.2	45.0	16.3	3.2	3.51
SUMB 40 U1 9	-18.7	11.8	47.1	16.9	3.3	3.94
SUMB 40 U1 10	-19.0	11.8	45.0	16.3	3.2	4.37
SUMB 40 U1 11	-19.0	11.7	45.5	16.5	3.2	4.80
SUMB 40 U1 12	-19.0	11.5	46.0	16.7	3.2	5.23
SUMB 40 U1 13	-19.1	11.3	44.1	15.9	3.2	5.66
SUMB 40 U1 14	-19.0	11.4	44.1	16.0	3.2	6.09
SUMB 40 U1 15	-18.8	11.3	45.6	16.5	3.2	6.52
SUMB 40 U1 16	-19.0	11.4	44.7	16.1	3.2	6.95
SUMB 40 U1 17	-18.8	11.4	45.0	16.2	3.2	7.38
SUMB 40 U1 18	-18.8	11.3	44.5	16.1	3.2	7.81
SUMB 40 U1 19	-18.8	11.3	45.5	16.4	3.2	8.24
SUMB 40 U1 20	-18.5	11.4	46.0	16.6	3.2	8.67
SUMB 40 U1 21	-18.2	11.7	44.7	16.0	3.3	9.10
SUMB 40 U1 mean	-18.9	11.5	45.2	16.3	3.2	
SUMB 41 M1 1	-21.1	11.1	40.5	14.6	3.2	0.93
SUMB 41 M1 2	-20.8	10.8	40.8	14.8	3.2	1.36
SUMB 41 M1 3	-20.6	10.9	42.3	15.4	3.2	1.79
SUMB 41 M1 4	-20.5	11.1	42.1	15.3	3.2	2.22
SUMB 41 M1 5	-20.6	11.0	41.1	14.9	3.2	2.65
SUMB 41 M1 6	-20.6	11.2	42.1	15.4	3.2	3.08
SUMB 41 M1 7	-20.5	11.1	41.6	15.1	3.2	3.51
SUMB 41 M1 8	-20.5	11.0	41.3	15.0	3.2	3.94
SUMB 41 M1 9	-20.4	10.8	41.7	15.2	3.2	4.37
SUMB 41 M1 10	-20.5	10.8	41.7	15.1	3.2	4.80
SUMB 41 M1 11	-20.4	10.7	41.8	15.1	3.2	5.23
SUMB 41 M1 12A	-20.5	10.5	41.5	15.0	3.2	5.66
SUMB 41 M1 13	-20.6	10.5	41.5	15.0	3.2	6.09
SUMB 41 M1 14	-20.6	10.7	41.9	15.1	3.2	6.52
SUMB 41 M1 15	-20.4	10.5	41.6	15.0	3.2	6.95
SUMB 41 M1 16	-20.5	10.7	42.6	15.4	3.2	7.38
SUMB 41 M1 17	-20.6	10.7	40.8	14.8	3.2	7.81
SUMB 41 M1 18	-20.5	11.0	41.0	14.7	3.3	8.24
SUMB 41 M1 19	-20.4	11.0	41.0	14.7	3.2	8.67
SUMB 41 M1 20	-20.5	11.1	40.7	14.5	3.3	9.10

SUMB 41 M1 21	-20.4	11.3	41.5	14.8	3.3	9.53
SUMB 41 M1 mean	-20.6	10.9	41.5	15.0	3.2	
SUMB 42 M2 1	-20.0	11.6	41.8	15.3	3.2	2.50
SUMB 42 M2 2	-19.8	11.4	42.2	15.6	3.2	3.30
SUMB 42 M2 3	-19.9	11.6	41.5	15.3	3.2	4.10
SUMB 42 M2 4	-19.6	11.6	41.5	15.2	3.2	4.90
SUMB 42 M2 5	-20.0	11.6	42.0	15.5	3.2	5.70
SUMB 42 M2 6	-19.9	11.8	42.4	15.6	3.2	6.50
SUMB 42 M2 7	-19.0	12.4	51.3	18.9	3.2	7.30
SUMB 42 M2 8	-18.7	12.6	41.4	15.2	3.2	8.10
SUMB 42 M2 9	-18.5	12.9	41.1	15.0	3.2	8.90
SUMB 42 M2 10	-17.8	13.3	41.5	15.1	3.2	9.70
SUMB 42 M2 11	-19.4	11.9	42.5	15.5	3.2	10.50
SUMB 42 M2 12	-20.1	11.8	41.1	15.0	3.2	11.30
SUMB 42 M2 13	-19.5	11.7	41.8	15.3	3.2	12.10
SUMB 42 M2 14	-19.7	11.8	43.2	15.8	3.2	12.90
SUMB 42 M2 15	-19.6	12.0	40.8	14.9	3.2	13.70
SUMB 42 M2 16	-19.1	12.1	42.0	15.4	3.2	14.50
SUMB 42 M2 17	-19.2	12.1	40.2	14.6	3.2	15.30
SUMB 42 M2 mean	-19.4	12.0	42.3	15.5	3.2	
SUMB 43 M2 1	-19.2	12.2	41.1	15.2	3.1	2.50
SUMB 43 M2 2	-18.5	12.5	41.4	15.7	3.1	3.02
SUMB 43 M2 3	-19.0	11.6	43.8	16.7	3.1	3.54
SUMB 43 M2 4	-19.2	11.6	35.5	13.4	3.1	4.06
SUMB 43 M2 5	-19.0	11.8	43.8	16.6	3.1	4.58
SUMB 43 M2 6	-18.9	11.5	42.3	16.1	3.1	5.10
SUMB 43 M2 7	-18.9	11.2	41.8	15.8	3.1	5.62
SUMB 43 M2 8	-18.6	11.3	42.1	15.9	3.1	6.14
SUMB 43 M2 9	-18.1	11.8	42.1	16.0	3.1	6.66
SUMB 43 M2 10	-17.7	12.4	43.2	16.3	3.1	7.18
SUMB 43 M2 11	-17.8	12.6	40.7	15.3	3.1	7.70
SUMB 43 M2 13	-18.0	13.0	42.4	16.0	3.1	8.74
SUMB 43 M2 14	-18.1	12.9	43.4	16.3	3.1	9.26
SUMB 43 M2 mean	-18.5	12.1	42.0	15.9	3.1	
SUMB 44 M2 1	-20.1	11.8	40.8	15.2	3.1	2.50
SUMB 44 M2 2	-19.4	12.1	43.3	16.2	3.1	3.37
SUMB 44 M2 3	-18.8	11.8	43.5	16.2	3.1	4.24
SUMB 44 M2 4	-18.8	11.4	42.4	16.0	3.1	5.11

SUMB 44 M2 5	-19.5	10.7	42.8	16.2	3.1	5.98
SUMB 44 M2 6	-19.9	11.2	42.0	15.8	3.1	6.85
SUMB 44 M2 7	-19.8	11.2	42.1	15.7	3.1	7.72
SUMB 44 M2 8	-19.9	11.0	42.2	15.8	3.1	8.59
SUMB 44 M2 9	-20.0	11.9	43.4	16.0	3.2	9.46
SUMB 44 M2 10	-19.9	11.8	41.8	15.6	3.1	10.33
SUMB 44 M2 11	-19.7	11.9	42.8	15.8	3.2	11.20
SUMB 44 M2 12	-20.0	11.7	42.2	15.7	3.1	12.07
SUMB 44 M2 13	-20.1	11.8	43.5	16.0	3.1	12.94
SUMB 44 M2 14	-20.1	11.9	39.6	14.3	3.2	13.81
SUMB 44 M2 15	-19.9	12.2	42.4	15.3	3.2	14.68
SUMB 44 M2 mean	-19.7	11.6	42.3	15.7	3.1	
SUMB 45 M1 1	-20.2	10.4	39.7	14.4	3.2	0.50
SUMB 45 M1 2	-19.4	11.0	40.2	14.5	3.2	1.10
SUMB 45 M1 3	-19.0	11.6	42.7	15.4	3.2	1.70
SUMB 45 M1 4	-18.8	11.9	40.8	14.7	3.2	2.30
SUMB 45 M1 5	-18.5	12.1	41.2	15.0	3.2	2.90
SUMB 45 M1 6	-18.8	11.9	45.7	16.6	3.2	3.50
SUMB 45 M1 7	-18.6	12.1	36.3	13.1	3.2	4.10
SUMB 45 M1 8	-19.0	11.8	41.0	14.7	3.3	4.70
SUMB 45 M1 9	-19.1	11.8	41.9	15.0	3.3	5.30
SUMB 45 M1 10	-19.0	11.7	45.3	16.2	3.3	5.90
SUMB 45 M1 11	-18.9	11.9	40.0	14.4	3.2	6.50
SUMB 45 M1 12	-19.2	11.8	40.0	14.2	3.3	7.10
SUMB 45 M1 13	-19.2	11.6	40.4	14.4	3.3	7.70
SUMB 45 M1 14	-19.2	11.8	41.6	14.6	3.3	8.30
SUMB 45 M1 15	-18.7	12.0	28.9	9.9	3.4	8.90
SUMB 45 M1 mean	-19.0	11.7	40.4	14.5	3.3	
SUMB46 M1 1	-19.0	12.2	40.8	14.7	3.2	0.50
SUMB46 M1 2	-18.5	12.3	39.2	14.3	3.2	0.92
SUMB46 M1 3	-18.9	11.8	38.3	14.0	3.2	1.34
SUMB 46 M1 4	-19.1	11.6	38.9	14.0	3.2	1.76
SUMB46 M1 5	-19.2	11.6	39.5	14.3	3.2	2.18
SUMB46 M1 6	-19.2	11.4	42.3	15.1	3.3	2.60
SUMB46 M1 7	-18.9	11.2	39.4	13.8	3.3	3.02
SUMB 46 M1 8	-18.8	11.3	39.4	13.9	3.3	3.44
SUMB 46 M1 9	-18.6	11.5	40.7	14.3	3.3	3.86
SUMB 46 M1 10	-18.4	11.7	39.0	13.5	3.4	4.28

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SUMB 46 M1 11	-18.2	12.2	39.4	13.9	3.3	4.70
SUMB 46 M1 12	-17.9	12.8	40.6	14.2	3.3	5.12
SUMB 46 M1 13	-18.5	12.9	40.8	14.0	3.4	5.54
SUMB 46 M1 mean	-18.7	11.9	39.9	14.1	3.3	

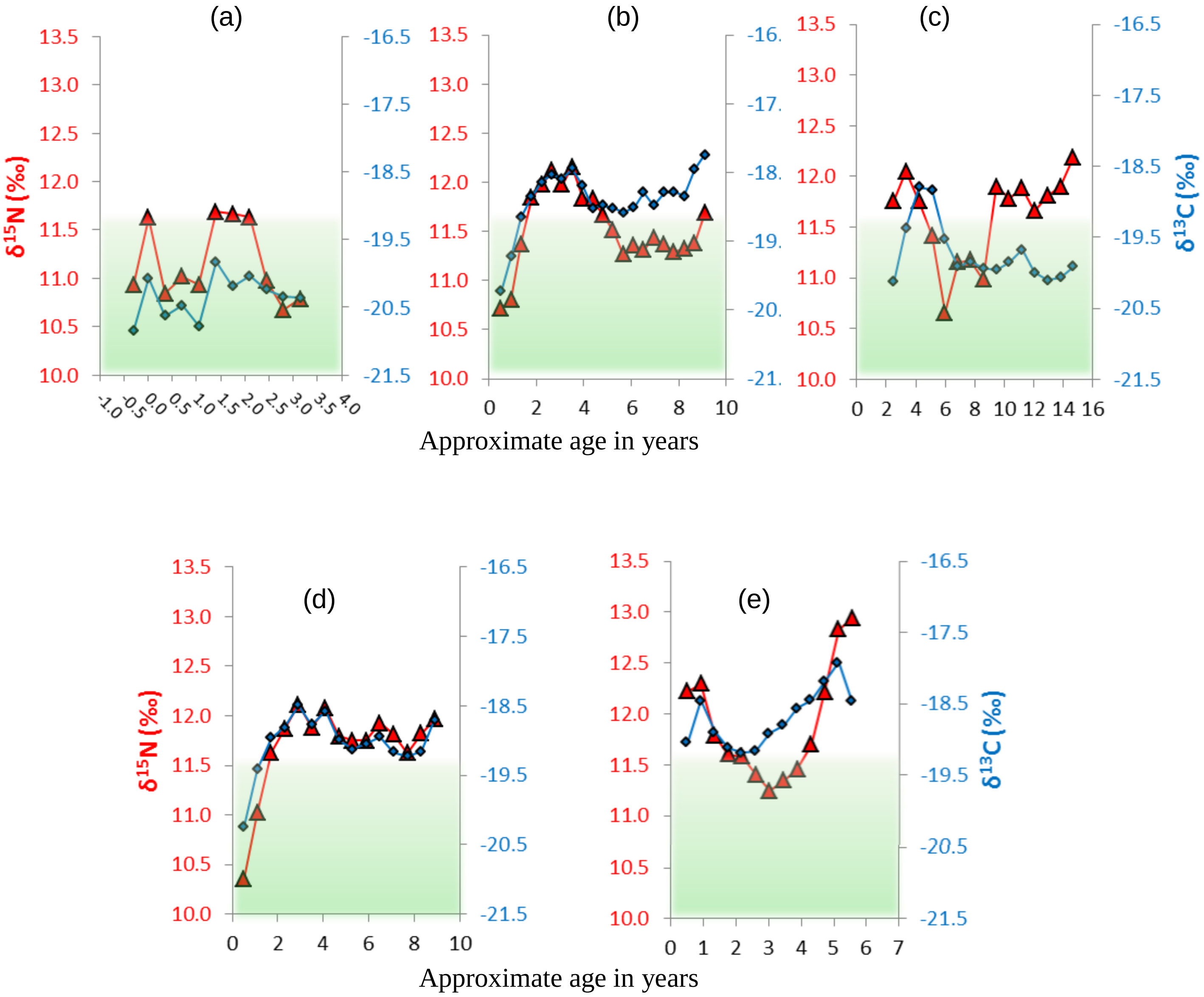

Figure S1. Carbon and nitrogen stable isotope ratios of the incremental dentine samples from a) SUMB-39; b) SUMB-40; c) SUMB-44; d) SUMB-45; and e) SUMB-46. The shaded green area at the bottom of each chart represents a purely terrestrial diet, based on the conservative limit of –19.1‰.

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