A multi-isotope, multi-tissue study of colonial origins and diet in New Zealand

Running Title: An isotopic study of colonial New Zealand life

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Abstract

Objectives: Colonial period New Zealand was lauded as a land of plenty, where colonists could improve their station in life and secure a future for their families. Our understanding of colonial experience, however, is often shaped by historical records which communicate a state-sponsored version of history. This study aims to reconstruct the lives of settlers using isotopic evidence from the colonial skeletons themselves.

Materials and Methods: We use skeletal remains from recently excavated colonial sites in Otago (South Island, New Zealand) to illustrate the information that can be gleaned from the isotopic analysis of individuals. We use $^{87}Sr/^{86}Sr$ to identify European settlers, and $\delta^{13}C$ and $\delta^{15}N$ from collagen and hair keratin, as well as dental enamel carbonate $\delta^{13}C$ to trace dietary change over their life-courses.

Results: Strontium isotope analysis shows that all adults in our sample are non-local. Dietary isotopes show that while most individuals had relatively consistent childhood diet, one individual with more rural origins had seasonal use of resources during childhood. While some members of the population seem to have increased their meat intake in the new colony most do not have clear evidence for this.

Discussion: We show the diversity of human experience in first generation New Zealanders both prior to emigration and in the new colony. Despite colonial propaganda claiming that circumstances in New Zealand were improved for all settlers, we have little evidence for this, aside from among individuals of potentially high status.

Keywords: Bioarchaeology, Colonial Archaeology, Australasia, Incremental dentine isotope analysis

Introduction

Colonial expansion by European powers heralded the start of modern globalization processes (Ballantyne 2010). Historical sources record the movement of people and goods, as colonists moved in search of new lands, new lives and new opportunities for wealth. However, there are recognized gaps in the historical record which mean that archival research alone cannot tell the full story of this period. Archaeology and bioarchaeological investigations of this time period can provide insights into historically less-visible processes such as bio-social adaptation to new environments, cultural relations, and the development of colonial identities (Croucher & Weiss, 2011; Guiry et al., 2018; Voss, 2008).

New Zealand was a part of this global colonial expansion, with whalers and sealers reaching its shores in the late 1700s, and missionary settlements beginning in the early 1800s (Anderson, 1998; Belich, 1996; Smith, 2014). More organized European settlement of New Zealand was spearheaded by the New Zealand Company from the 1840s, after the signing of the Treaty of Waitangi (Ballantyne, 2010). This document aimed to both guarantee the rights of the indigenous Māori people of New Zealand and allow settlement by Europeans (Pākehā New Zealanders) (The Treaty of Waitangi/ Te Tiriti o Waitangi, 1840). The events of this period have left a lasting legacy and shaped the experiences of both Māori and Pākehā. The choices colonists made, their impact on the Māori people, and their alteration of the New Zealand environment continue to have important implications for New Zealand politics and identity today (Bell, 2006; O'Sullivan, 2008; Spoonley, 2015).

Our understanding of life in the New Zealand colony has been heavily shaped by historical sources. There are, however, "gaps, silences and contradictions" (Ballantyne 2012: 283) in the historical record, particularly surrounding the everyday lives of the colonists. Although the wealthy leaders of the colony are well described, the lives and hardships of the common people who came seeking better living conditions are more-poorly understood. Colonial propaganda of the time promotes New Zealand as a land of plenty, where people were healthier, and the potential for social advancement was high (Anon, 1853; Butler Earp, 1853; Durrer, 2006; Sargent, 2001). Historical sources, however, tend to make generalizations in service of a bigger picture of New Zealand society (Ballantyne, 2012), the individual lives of the people who made up grassroots colonial settlements are often missing from the narrative.

The archaeological record can help to address these gaps in the historical record. New Zealand is a leader in the field of colonial archaeology (e.g. Flexner, 2014) with the study of both material culture and landscape archaeology well-established in the country. Colonial material culture studies have given insight into colonial identity and acculturation (Ritchie, 1986), consumption patterns (Adamson & Bader, 2013), importation habits (Adamson & Bader, 2013; Petchey & Innanchai, 2012) and use of space (Middleton, 2007; Smith, 2014; Smith & Garland, 2012). Studies of landscape use and connectedness also give insight into the intersecting lives of Māori and Pākehā in the earliest periods of European settlement of New Zealand (Bedford, 2013; Holdaway & Wallace, 2013; Smith, 2019). Despite this, excavation and study of the skeletal remains of colonial settlers has been limited to salvage excavations undertaken due to development (Best, Furey, & Campbell, 2006; Petchey, Buckley, & Scott, 2018; Trotter & McCulloch, 1989).

Recent research-led excavations at the now defunct cemetery of St. John's, Milton (Figure 1) have yielded multiple individuals, who are either European-born settlers or first generation Pākehā New Zealanders (Petchey, Buckley, Kinaston, & Smith, 2017). The biological information contained within the skeletons of these individuals has the potential to reveal previously unknown aspects of the colonial experience. In combination with historical and social information, skeletal analyses can provide a more nuanced and holistic picture of life in the New Zealand colony. For example, bone dietary isotope analysis from these individuals has already shown that settlers retained some aspects of the traditional British diet in the form of a reliance on terrestrial crops and domestic animals. However, the early settlers likely supplemented their intake of farmed meat with the readily-available wetland resources of the surrounding area, resulting in a mixed dietary strategy (King et al., in press a). This pattern of wild resource supplementation has also been observed in colonial contexts elsewhere, for example in various North American contexts (Guiry et al., 2018; Reitz & Waselkov, 2015). Changing subsistence strategies to buffer against resource vulnerability in new environments can result in the development of regionally specific colonial food identities (as per Owen, Casey & Pitt, 2017).

In this study, we build on these first isotopic results from colonial New Zealand (King et al., in press a) to reconstruct dietary change through the life course of some of the first European settlers to arrive in rural Otago (South Island, New Zealand). Different human tissues form at specific times, making it possible to look at isotopic evidence for diet and stress in tissues with different formation times to build a relatively complete picture of a person's life (Beaumont & Montgomery, 2016; King et al., 2018; Knudson, Pestle, Torres-Rouff, & Pimentel, 2012; Cox, Sealy, Schrire & Morris, 2010; Sealy, Armstrong & Schrire, 1995).

In this study we examine colonial origins using $^{87}Sr/^{86}Sr$ isotope analysis of dental enamel. Childhood diet, including weaning trajectory, was assessed using analysis of incremental sections of dentinal collagen as well as dental enamel carbonate; bone collagen was used as a general proxy for adult diet; and hair was analyzed incrementally to examine changes leading up to time of death.

Taken together, evidence from each of these tissues will allow us to investigate:

a) Whether adults in St John's Milton have their origins elsewhere, and are therefore probable European settlers;
b) what childhood diet at 'home' was like for these individuals;

c) whether there are changes in dietary isotope ratios between a childhood spent at 'home' and adulthood in the colony and what the cause of any differences might be; and
d) whether there is any isotopic evidence for physiological stress at any point in the lives of these individuals.

We aim to compare life at home with life in the colony by obtaining time-resolved, isotopic knowledge of life conditions and combining it with evidence from the historical record. We bring to light individual life histories, and aim to address gaps in the historical literature by describing the experiences of 'grassroots' colonial New Zealanders.

Archaeological context

The samples used in this study derive from the colonial cemetery of St. John's Anglican Church, Milton (Figure 1). This cemetery sample was excavated as part of a collaborative project with a local historical group (TP60), with the aim of establishing the boundary of the cemetery and finding the unmarked graves within the currently fenced portion of the cemetery (Petchey et al., 2017). St John's cemetery, Milton was open from 1860 to 1926, although the vast majority of interments were made between 1860 and 1880 (Findlay, 2016). The first European settlement of the Tokomairiro plains (upon which Milton lies), occurred in 1850 (Sumpter & Lewis, 1949), making it likely that the individuals analyzed in this study were either first European settlers or first generation Pākehā New Zealanders. This is also consistent with mtDNA results obtained from several of the burials, which all belonged to European haplogroups (unpublished data). St. John's, Milton provides an extremely interesting sample for study, as some of the burials yielded readable coffin plates (Petchey et al., 2017), meaning that some individuals are identifiable and historical records of their lives can be used to complement the biological information. The named burials uncovered in this project date exclusively to the 1870s.

[Figure 1 here]

St. John's is also an interesting site in terms of preservation. It lies upon a flood plain, and most of the burials found lie outside of the currently marked cemetery on neighbouring farmland, where farm-waste dumping has been common. In fact, a later-dug farm drainage ditch truncates one of the excavated burials. The excavation showed that many of the burials on site lie beneath the water table. These conditions have resulted in unusual preservation of burials (King et al., in press b). Generally, bone and dentine are not well preserved, especially in children, but keratinous tissues (such as hair and nails) survive well. This means that most infants and children are represented by dental enamel and hair only. Adult bone and tooth material survives better, probably because of its more mineralized nature (Buckberry, 2018; Lewis, 2007). A lack of bone preservation in some burials limits isotopic reconstruction of population diet. However, in this study we highlight how the preservation of tissues that are not normally present in archaeological sites can give unprecedented insight into the individual lives of settlers.

Background – reconstructing colonial life histories using isotopic evidence

In this study we use strontium isotope analysis ($^{87}Sr/^{86}Sr$ ratios) to assess whether adults in the SJM sample were non-local, and likely to be European settlers to the area. We then use carbon stable isotope ratios in dental enamel apatite ($\delta^{13}C_{carb}$), and both carbon ($\delta^{13}C_{col}$) and nitrogen ($\delta^{15}N$) isotope ratios in bone and dentinal collagen and hair to study diet through the lifetime of individuals (Figure 2).

[Figure 2 here]

Strontium isotope analysis is well-established as a method for investigating past mobility (Bentley, 2006; Montgomery, 2010). The ratio of ^{87}Sr to ^{86}Sr varies in nature from region to region based on underlying rock type, age of rocks and various physiological processes which release strontium from bedrock into the biosphere. Interpretation of strontium isotope results requires good knowledge of local geological and bioavailable strontium, as well as knowledge of these factors in possible regions of origin for the individuals. In New Zealand strontium isotope baseline work is in its infancy, but foundations have been laid by Duxfield et al. (in review), whose synthesis of geological and bioavailable data from the Otago region suggests that Milton lies in a region of expected $^{87}Sr/^{86}Sr$ of 0.7066-0.7083. Those falling outside of this range can therefore be identified as migrants to the Otago region. During this period the most likely regions of origin for migrants are the UK. Bioavailable baseline work in the UK has been thoroughly conducted by Evans et al. (2010), and their maps may assist in interpreting region of origin for our settlers.

Carbon and nitrogen isotopic ratios in collagen are useful proxies for human diet because they are derived from resources eaten by an individual (Schoeninger & DeNiro, 1984). Terrestrial carbon isotope ratios vary based on the plant type at the base of the foodweb. Differences in the photosynthetic pathway between C_3 plants (e.g. wheat, rice and legumes) and C_4 plants (e.g. maize, millet and sugarcane) result in differences in tissue $\delta^{13}C$ values of their consumers (Ambrose & Norr, 1993). In both New Zealand and Britain, almost all commonly eaten plant resources use a C_3 photosynthetic pathway, but maize (a C_4 crop) was grown in the North Island of New Zealand (Rhodes & Eagles', 2012), and sugar (a product of the C_4 crop, sugarcane) was imported into both Britain and New Zealand, with the first New Zealand sugar refinery set up in 1882 (Hawera & Normanby Star, 1882).

Nitrogen, on the other hand, can be used as a reflection of the proportion of meat consumed because $\delta^{15}N$ values increase with each step in the food chain (DeNiro & Epstein, 1981; Minagawa & Wada, 1984). Both $\delta^{13}C$ and $\delta^{15}N$ also have characteristic values when marine resources are consumed, with higher $\delta^{13}C$ values and much higher $\delta^{15}N$ values recorded in marine systems (Chisholm, Nelson, & Schwarcz, 1982; Minagawa & Wada, 1984). In New Zealand, freshwater fish and birds have intermediate values, falling between terrestrial and marine carbon, partially due to the marine migration of some endemic freshwater species. These differences are summarized on Figure 3, showing expected $\delta^{13}C$ and $\delta^{15}N$ values for typical foods consumed in colonial New Zealand.

[Figure 3]

Childhood diet:

In this study we reconstruct diet at 'home' prior to emigration, looking at childhood feeding practices using serial sectioning of dentine and examining isotopic changes throughout tooth formation. This allows us to characterize the weaning process of individuals or establish dietary profiles in different stages of childhood. The weaning process is a dietary shift and $\delta^{13}C_{col}$ and $\delta^{15}N$ values undergo characteristic changes, decreasing by about 1‰ and 3‰ respectively as weaning progresses – providing the supplementary foods are isotopically similar to the mother's diet (Fuller, Fuller, Harris, & Hedges, 2006; Tsutaya & Yoneda, 2015). This is because while breastfeeding an infant is effectively consuming the mother's protein in the form of breastmilk, and thus appears a trophic level higher isotopically (Fuller et al., 2006). As breastmilk is increasingly supplemented with other food resources through the weaning process, infant $\delta^{13}C_{col}$ and $\delta^{15}N$ will slowly shift to values more typical of the adult diet. Thus we might expect the teeth and hair of infants and children to carry isotopic traces of the weaning process, in addition to the early forming teeth of adults, such as the first molar. The known incremental growth rates of tissues such as teeth and hair means that this weaning process can also be timed, by establishing when isotopic ratios change (Beaumont & Montgomery, 2015).

We also use apatite carbonate $\delta^{13}C$ values of four individuals (those with the best-preserved enamel: B4, B6, B11 and B29) alongside dentinal collagen $\delta^{13}C$ values to better describe childhood diet. We focus on teeth forming during the weaning period (incisors and canines), but enamel was sampled from the cervical area of the crown to avoid input of breastmilk isotopic values. These enamel values are correlated with collagen values with roughly the same age of formation (AlQahtani, Hector, & Liversidge, 2010). Enamel $\delta^{13}C_{carb}$ values are useful because the $\delta^{13}C$ offset between diet and collagen varies substantially based on the composition of the diet. When these constituents are unknown, as they are in this instance, $\delta^{13}C_{carb}$ values from dental enamel apatite can be used as a proxy for whole diet (i.e. all the macronutrients- carbohydrates, lipids and proteins), allowing us to better characterize overall diet. Bivariate regression models using enamel carbonate and dentinal collagen values can therefore allow the visualization of both the ratio of C_3 to C_4 foods, and the amount of C_3 and C_4 protein vs. marine protein in the diet (Froehle, Kellner, & Schoeninger, 2010).

Dietary change once in the colony:

Examining differences between childhood and adult diet is theoretically possible through comparison of dentine, bone and hair isotope ratios. Depending on the age of tooth formation, dentinal $\delta^{13}C_{col}$ and $\delta^{15}N$ values will represent infant and childhood diet, bone collagen $\delta^{13}C$ and $\delta^{15}N$ values in adults generally represent adult life, and hair values represent the last months of life. However, interpretation of these differences is complicated if an individual relocates to a new environment between childhood and adulthood (as is the case for our early New Zealand colonists). As noted in King et al. (in press a) there are differences in baseline foodweb isotope ratios between the UK and New Zealand. This means that changes to isotope ratios may not necessarily correspond with dietary changes, but may instead reflect different land use patterns and agricultural practices in the colony. Nineteenth century baseline studies from the UK are limited (see Fisher & Thomas, 2012; Müldner & Richards, 2005 for exceptions), but do show that the environmental differences between home and the colony are around 2‰ ($\delta^{15}N$). We therefore restrict interpretation of dietary change to individuals who have differences of over 2‰ between childhood and adult isotope ratios. We argue below that differences of this magnitude are likely to reflect real dietary change.

Examining episodes of stress isotopically:

Recent research suggests that changes in $\delta^{13}C_{col}$ and $\delta^{15}N$ values may also reflect periods of nutritional stress (Beaumont & Montgomery, 2016; Fuller et al., 2005; Mekota, Grupe, Ufer, & Cuntz, 2006; Reitsema, 2013). When the body undergoes starvation, it begins to catabolize its own tissues to make up for energy deficits. This causes increased $\delta^{15}N$ and decreased $\delta^{13}C_{col}$ values (Beaumont, Montgomery, Buckberry, & Jay, 2015; Fuller et al., 2005). However, Beaumont & Montgomery (2016) suggest that stress may also manifest as a shift to higher $\delta^{15}N$ values, with unchanging $\delta^{13}C$ values. It is possible that if famine conditions were experienced by people in the colony, they might be visible in incrementally forming tissues such as hair or dentine (Beaumont & Montgomery, 2016; Mekota et al., 2006). This is particularly relevant for those in catabolic states in the lead up to death, whose hair would likely isotopically capture the change in their metabolic status.

Methods and Materials

This study focuses on the adults from St. John's Milton with more than one tissue available for study (n=7, Table 1).

We focus on tracing the lives of the settlers through the integration of isotope data from teeth (which form during childhood), bone (which represent a homogenized adult diet) and hair (which forms up to time of death) (Figure 2). This is the first time that serial isotopic data has been obtained from a first-generation colonial or a New Zealand context. Although the number of individuals analyzed is small, they have yielded around over 100 data points between them (average of 16 per person), highlighting the amount of information that can be obtained from just a few individuals when detailed multi-tissue and serial approaches are undertaken.

Of the adults at St John's Milton, three have preserved and legible coffin plates, we thus have names and historical information associated with them (B4, B6 and B21). Out of respect for their descendants we do not name them here, but have been granted permission to share relevant historical details to support our isotopic results. Descendant groups have also been kept informed of research results throughout the process. The age and sex of the other adults of unknown identity was estimated using established osteological standards (Buikstra & Ubelaker, 1994). The age and sex of the named individuals was also estimated using these methods to corroborate information given on their coffin plates, but ages listed in Table 1 used are taken from their death registrations. Each of the different tissues present in the burials were analyzed isotopically.

Burial Number	**Age**	**Sex**	**Dentine sampled**	**Enamel sampled**	**Other tissues sampled**	**Known identity?**
B4	44 years	M	Mandibular LM3	Mandibular LM3	Bone collagen (temporal)	Yes
B6	36 years	F	Maxillary I1	Maxillary I1	Bone collagen (lumbar vertebra)	Yes

B11	Middle aged adult	M	Maxillary RC	Maxillary RC	Bone collagen (rib) Hair	No
B13	Adult	M	No dentine present	Max. molar frags	None	No
B21	42 years	M	Mandibular LC	Mand LC (for Sr only)	Bone collagen (ulna cortical bone) Hair	Yes
B23	Young adult	F?	Mandibular LC	No	Bone collagen (femoral cortical bone) Hair	No
B29	Adult of unknown age	F	Mandibular I2	Mandibular I2	Bone collagen (thoracic vertebra)	No

Table 1: Individuals in this study, tissues sampled and demographic information.

Tooth samples:

Teeth form during infancy and childhood and do not remodel through life (Hillson, 1996). Isotopic ratios in teeth, therefore, reflect childhood diet and health. They may reveal different natal origins, childhood diet, and weaning patterns (Lee-Thorp, 2008; Montgomery, 2010; Tsutaya & Yoneda, 2015). In order to identify both weaning patterns and childhood diet, teeth which form during early childhood and continue forming throughout much of childhood were targeted for all individuals (e.g. permanent canines and incisors) (AlQahtani et al., 2010; Hillson, 1996). For those individuals with poor anterior dental preservation (e.g. B4) the best-preserved tooth was used, in this case a permanent M3, which forms between the ages of 8.5 and 23 years (AlQahtani et al., 2010). This tooth will not, therefore, record variation relating to weaning and early childhood diet. For the incremental dentine analyses each tooth was half-sectioned longitudinally using a dental drill and half of the tooth prepared for carbon and nitrogen isotope analysis. A chip of crown enamel (approx. 10mg) was removed for strontium isotope analysis. A second enamel sample was removed as powder using a diamond burr for carbonate analysis. The position in the crown sampled varied depending on the tooth type. For early forming teeth, such as canines and incisors, only the cervical part of the crown was powdered, to minimize input from enamel formed during the breastfeeding period. For later-forming teeth, such as the M3 sampled, a track from top to bottom of the crown was burred.

All enamel samples were mechanically cleaned of particulates adhering to the external surface of the enamel prior to sampling, and dentine was similarly removed using a diamond burr. Half-sectioned teeth to be demineralised for incremental collagen analysis were also cleaned using a diamond bur prior to demineralisation.

Bone samples:

Bone remodels throughout life and bone turnover rates vary depending on the bone. Highly trabecular bones such as ribs turnover relatively quickly, generally over a period of 10 years or less (Fahy, Deter, Pitfield, Miszkiewicz, & Mahoney, 2017). Long bones, and bones of the skull have longer turnover periods, and in adults may retain some collagen from adolescence (Hedges, Clement, Thomas, & O'Connell, 2007). Bone collagen isotope ratios therefore reflect an integrated dietary signal from the period of bone turnover. In this study we preferentially sampled faster remodelling elements such as ribs and the bones of the forearm, however in one instance (B4) preservation issues forced us to sample a slower-remodelling bone (the temporal). For all the bone samples, 200mg were removed using a dental drill with diamond cutting blade. The periosteal and medullary surfaces were cleaned of particulates using a dental burr prior to collagen extraction for carbon and nitrogen isotope analysis.

Hair samples:

Human hair grows up to time of death, at a rate of approximately 1 cm per month (O'Connell & Hedges, 1999). This means that 1 cm increments of hair represent one month of time, with increment closest to the scalp forming near to time of death. As only around 88% of hairs will be in anagen (or growth) phase at any given time, a group of 10-15 aligned hair strands were sample for each individual. This controls for the presence of hair in telogen (or static) phase (O'Connell & Hedges, 1999; Webb, White, Van Uum, & Longstaffe, 2015). These hair strands were kept in their *in vivo* orientation, with hair follicles aligned at the top of each strand. Aligned strands were sectioned in 1cm increments using a sterilized surgical steel scalpel and placed into individual microtubes.

Foodweb data:

There is no current faunal isotopic baseline for colonial New Zealand contexts. Our samples, being from a cemetery population do not have midden associated with them. Most other excavations conducted on colonial New Zealand contexts have been done commercially, and New Zealand commercial archaeology guidelines do not require archaeofaunal material to be retained or analyzed. For the purposes of this investigation we therefore use modern baseline data, corrected for the effect of fossil fuels on carbon isotope ratios (Francey et al., 1999) for reference (Supplementary Table 1). We acknowledge that this will be an imperfect proxy for colonial contexts, and therefore take only a broad approach to dietary interpretation.

Strontium isotope analysis:

Strontium isotope analysis was undertaken at the Arthur Holmes Isotope Geology Laboratory, Dept. of Earth Sciences, Durham University. Sr separation used the protocols laid out in Font et al. (2008), with enamel chips dissolved in 3M HNO_3 and passed through Eichrom Sr- Spec exchange resin columns. Isotope measurements were carried out by Multi-Collector Inductively Coupled Plasma Mass Spectrometry (MC-ICP-MS) using a ThermoFisher Neptune MC-ICP-MS. Samples were analysed in a single session during which the average $^{87}Sr/^{86}Sr$ value and reproducibility for the NBS987 reference material was 0.710265±0.000009 (2σ; n=8). Data in table 2 are renormalized to an accepted value for NBS 987 of 0.71024. Total procedural blanks (n=2) were analyzed alongside tooth samples with a mean blank of 64±9 (1SD) pg Sr.

Bioapatite isotope analysis:

Carbon isotopic analysis of dental enamel was conducted at the Max Planck Institute for the Science of Human History, Jena, Germany. Enamel chips were ground to a powder using an agate pestle and mortar. Enamel powders were pretreated to remove organic and secondary carbonate contaminants. This involved washing in 1% NaClO, followed by three rinses in MilliQ H_2O. 0.1M acetic acid was then added for 10 minutes prior to rinsing again 3 times in MilliQ H_2O. Samples were then freeze dried. For isotopic analyses samples were weighed out into 12 ml borosilicate glass vials and sealed with rubber septa. Following reaction with 100% phosphoric acid, gases evolved from samples which were then analysed for their stable carbon and oxygen isotope measurements using a Thermo Gas Bench 2 connected to a Thermo Delta V Advantage Mass Spectrometer at the Department of Archaeology, Max Planck Institute for the Science of Human History.

$\delta^{13}C_{carb}$ values were calibrated against International Standards (IAEA-603 ($\delta^{13}C = 2.5$); IAEA-CO-8 ($\delta^{13}C = -5.8$); USGS44 ($\delta^{13}C = -42.2$)) using a three-point calibration methodology. Replicate analysis of in-house MERCK standards suggests that long-term machine measurement error is *c.* ± 0.1‰ for $\delta^{13}C$. Overall measurement precision was determined by analyzing repeat extracts from an in-house bovid tooth enamel standard that was prepared alongside the samples to determine the impacts of pretreatment (n = 20, ± 0.2‰ for $\delta^{13}C$).

Collagen extraction:

Collagen from half-sectioned teeth was extracted using a modified Longin method (Longin, 1971). Bone fragments and the half-sectioned tooth were placed in 0.5M HCl until demineralized. Then teeth were cut into 1mm increments using a sterilized surgical scalpel following the method of Beaumont et al. (2013); each increment was placed in its own labelled microtube. Bone and dentine collagen was gelatinized by heating in a pH3 HCl solution at 70°C for 24-48 hours. Gelatinized collagen from bone samples was filtered using Ezee filters (Elkay, UK) and then lyophilized. Gelatinized increments were centrifuged prior to lyophilization, rather than filtered.

Results from dentinal collagen analysis were compared to previously published bone collagen results from the same individuals (King et al., in press a) in order to compare adult (bone collagen) to childhood (dentinal collagen) diet.

Hair analysis:

Hair increments were cleaned via a process of solvent washing. Each microtube was filled with a 2:1 methanol:chloroform mix, and sonicated for 20 minutes before decanting the solvent (O'Connell & Hedges, 1999). This process was repeated until the solvent remained clear after sonication, and no obvious particulates remained adhering to the hair. The potential for diagenetic change to hair structure and chemistry was assessed using Scanning Electron microscopy prior to analysis. For each individual five strands of 1cm length were chosen for visual assessment. These were mounted on aluminium stubbs using double sided carbon tape and coated in palladium. SEM was performed using a JEOL FE-SEM6700 At Otago Micro and Nanoscale Imaging (Otago University) at 5kV accelerating voltage. Hair preservation was assessed using the standards described in (Wilson, Dodson, Janaway, Pollard, & Tobin, 2010). All hair examined was found to be relatively well preserved. Most had intact cuticles, all displayed circular cross-sections indicating intact cortex and there was minimal microbial pitting (Figure 4).

[Figure 4 here]

All hair increments were rinsed in 18 MΩ water and allowed to air-dry prior to weighing into tin capsules for isotopic analysis.

Both collagen and hair samples were analyzed using a Costech Elemental Analyzer connected to a Thermo Delta V Advantage isotope ratio mass spectrometer at Durham University. Stable carbon isotope ratios were corrected for ^{17}O contribution, and both carbon and nitrogen isotope results are reported in delta notation as $\delta^{13}C$ and $\delta^{15}N$. Isotopic accuracy was monitored through repeat measurements of standards (USGS 40, USGS 24, IAEA 600, IAEA

N1, IAEA N2). Analytical uncertainty in carbon and nitrogen isotope analysis was typically < 0.1‰ for both repeat measures of standards and samples.

Collagen quality was assessed using standard parameters ($C:N_{atomic}$ = 2.9–3.6; C (wt %) = 30–50; and N (wt %) = 10–16), with hair having a slightly larger range of allowable ($C:N_{atomic}$ = 2.9 – 3.8) (O'Connell & Hedges, 1999).

Results

All collagenous tissues analyzed yielded good quality collagen results, with the exception of the tooth of B23, which failed to yield enough collagen for analysis. Full isotopic results from each tissue/increment are presented in Supplementary Table 2.

Assessing adult origins using $^{87}Sr/^{86}Sr$:

Strontium isotope results are presented in Table 2 and Figure 5 relative to the local geological and bioavailable Sr baseline in Milton (Duxfield et al., in review). All individuals fall outside of local values, supporting our interpretation that all adults in the sample are colonial settlers. Most individuals have very similar $^{87}Sr/^{86}Sr$ isotope values (range = 0.70905-0.70927), excepting B4 who has a ratio of 0.71191.

[Figure 5 here]

Assessing childhood diet using dentinal collagen and dental enamel apatite:

Results of dental enamel $\delta^{13}C$ (Table 2) and dentine $\delta^{13}C$ (Supplementary Table 2) are reported in Figure 6 with reference to the bivariate regression lines established by Froehle et al (2010). This compares enamel carbonate samples taken from the lower portion of the crown, and mean dentine incremental values from the same crown position (i.e. they are broadly taken as representing the same period of life).

[Figure 6 here]

Results from SJM clearly indicate that childhood diet for the individuals analyzed was C_3-based with minimal input from C_4 or marine dietary sources.

Individual	$^{87}Sr/^{86}Sr$	2SE	dental enamel $\delta^{13}C$ (‰, VPDB)	Std. Dev
SJM B4	0.71191	0.00001	-14.1	0.1
SJM B6	0.70934	0.00001	-14.1	0.1
SJM B11	0.70905	0.00001	-12.8	0.1
SJM B13	0.70911	0.00001	-13.1	0.1
SJM B21	0.70926	0.00001	Insufficient material for analysis	
SJM B29	0.709270	0.00001	-12.5	0.1

Table 2: Results of dental enamel isotopic results ($^{87}Sr/^{86}Sr$ and $\delta^{13}C$ values in enamel carbonate).

Changes to diet through life using $\delta^{13}C$ and $\delta^{15}N$ values in tooth, bone and hair of adults:

Individual dietary isotope profiles for all of the adults are given in Figure 6. This figure combines data from teeth (early life), bone (average adult diet) and, where available, hair (leading up to time of death) for each individual. Hair values have been corrected for the established offsets (approximately +1.4‰ $\delta^{13}C$, +2‰ $\delta^{15}N$) between hair and collagen (Caut, Angulo, & Courchamp, 2009; Drucker, Bridault, Hobson, Szumae, & Hervé, 2008), making values more directly comparable.

[Figure 7]

All individuals analyzed have bone collagen $\delta^{15}N$ values that are lower than their latest childhood/early adulthood values, though the bone values for B4 and B29 fall within the range observed in dentine.

The individuals with hair available for analysis have variable trends in $\delta^{15}N$ and $\delta^{13}C$ values at the end of life. Burial 23 and, to a lesser extent, B21 have corrected hair values that are higher than their bone values. Burial 11 on the other hand has a shift to lower $\delta^{15}N$ and higher $\delta^{13}C$ values. These differences between hair and bone may indicate small dietary shifts close to the end of life, or are perhaps reflective of isotopic manifestations of stress. We discuss these possible interpretations in the following sections.

Discussion

With a sample size of only seven individuals we cannot comment on population-wide phenomena in the colony, but we can give unique insight into the personal experiences of individuals. Here, we combine the 'isotopic biographies' established in this study with historical data to build a more nuanced picture of colonial life-experience.

Colonial origins:

Individuals in the SJM sample have very similar $^{87}Sr/^{86}Sr$ values (around 0.7090), indicating origins in similar geological areas, though not necessarily the same place. This aligns well with isotopic colonial origin studies conducted in Australia (e.g. Owen & Casey, 2017), likely reflecting the similar background of colonial populations in general. The exception to this is B4 ($^{87}Sr/^{86}Sr$ = 0.71191). B4 is an identified individual in the sample, the town doctor who originally hailed from southern Germany (Findlay, 2016). His higher $^{87}Sr/^{86}Sr$ ratio suggests his natal town was likely situated in an area of old felsic rock type (Figure 8). historical records suggest that most other individuals in the cemetery came from the United Kingdom. Previous biosphere strontium research in the UK suggests that values around 0.7090 may correspond with multiple areas of origin in the UK, shown visually on Figure 8. With all of these individuals most likely to have been first generation settlers it is therefore possible to address the question of dietary variation between childhood and adulthood.

[Figure 8 here]

Childhood diet prior to emigration:

By combining dental enamel carbonate and dentinal collagen $\delta^{13}C$ values we are able to better characterize childhood diet and find that, post-weaning, diet appears to have been heavily C_3-based for all analyzed individuals (Figure 5).

Although childhood diet is broadly similar, there are differences in actual isotope ratios displayed by each individual during childhood (Figure 9). For example, B29 has an average childhood dietary $\delta^{15}N$ value (after 3 years of age) of 13.3‰, while all other individuals have childhood $\delta^{15}N$ values of 11.9 – 12.2‰. B29's childhood (dentine) stable carbon isotope values are also higher than others in the sample (-19.0‰ vs. -19.9 to -19.5). In combination, these differences suggest that B29 may have had a diet containing more marine fish than other individuals, although we do stress that this interpretation is tentative as we cannot take into account the baseline values in B29's place of origin and whether or not they are different to others in the sample.

[Figure 9 here]

Breastfeeding and weaning practices:

In addition to bulk-sampled evidence of diet (from bone collagen), incrementally sampled dentinal collagen data allows us to assess how childhood diet changed through time. Overall, those studied appear to have had quite different dietary trajectories during childhood.

B11 is the only individual to display clear evidence for the weaning process with $\delta^{15}N$ values gradually decreasing between 9 months and 3.5 years of age (when breastmilk consumption had presumably dropped to less than 10% of dietary intake (Halcrow et al., 2018)). After weaning, however, his diet changed to higher trophic level resources (indicated by $\delta^{15}N$ values that are higher than breastfeeding values). More difficult to see are the weaning signals in B21 and B6. $\delta^{15}N$ values in these individuals continue to decrease until the age of 5, which would represent very extended breastfeeding. Usually, however, $\delta^{13}C$ values decrease in parallel with $\delta^{15}N$ during weaning (unless being weaned onto a different food to the mother). For both B6 and B21, their $\delta^{13}C$ values decrease until 2.3 and 2.2 years respectively, and then cease to echo the decrease in $\delta^{15}N$ values. We therefore consider it most likely that these ages represent time of weaning completion.

B29 is unusual in that there is no evidence for weaning in her isotopic profile, suggesting either that she was never breastfed, was fully weaned prior to the first datapoint at 9 months of age, or that other factors are interacting with her isotope ratios, effectively masking the effect of weaning. This is possible if the individual was weaned onto a higher trophic level food source than the mother's typical diet, for example seafood gruel (King et al., 2018), or if physiological stress kept $\delta^{15}N$ values 'artificially' high. Interpretation of B29's isotope ratios is complicated by osteological evidence of childhood developmental pathology. It may be that these early-life issues resulted in the artificial raising of her $\delta^{15}N$ values during weaning. If her lack of a weaning signal does indicate a complete lack of breastfeeding or weaning prior to 9 months, then her infant feeding experience was very different to that observed in the other individuals.

Historical evidence does suggest that Victorian weaning practices varied widely. Some sources suggest that lower-class families were likely to breastfeed for longer, with breastfeeding acting as a contraceptive as it suppresses ovulation (Fildes, 1986). This thus reduced the risk of further pregnancy and another child that they could not afford to feed. However, the very poorest families were likely to have to supplementary feed and wean earlier because of maternal ill-health or starvation (Fildes, 1998). In richer families, earlier weaning was preferred and planned for, with completion of weaning by 10 months suggested by fashionable sources of the period (Fildes, 1986). Though wet-nursing was common in the 18th century, in the 19th century wealthy families were more likely to cut breastmilk from the child's diet very early, instead preferring artificial (supplementary) feeding by nannies (Fildes, 1998). Potential early weaning in B29 may, therefore indicate either wealth or poverty in childhood. Though both are possible we consider wealthy origins more likely. B29's burial was associated with ornate coffin furniture made from high quality metal, suggesting wealth in later life. It is possible that B29's social status in the colony was dramatically different to her status in early life, New Zealand was considered a land of opportunity after all. Perhaps more likely though is that wealth at 'home' translated to wealth in New Zealand, and her breastfeeding (or lack thereof) was a result of following fashions for artificial feeding.

Changes to diet through childhood:

Dentinal data from 3 years of age onwards likely represents a post-weaning childhood diet for all individuals. All individuals studied had very little variation in $\delta^{15}N$ and $\delta^{13}C$ values between the ages of 3-9 years of age, likely indicating dietary consistency over this period. Burial 29 and B21 in particular have extremely similar values (variation <0.5‰) between 5-9 years of age. Burial 6 has the highest amount of childhood variation in $\delta^{15}N$ and $\delta^{13}C$ values, with $\delta^{15}N$ values oscillating by around 1‰ every 6 months or so. While this is not a large-scale change it may indicate that her childhood diet varied systematically, perhaps reflecting seasonal differences in resource availability. Burial 6 is an identified individual who hailed from Caithness, Scotland. It is possible that her rural Scottish diet was more seasonal than others from Milton, the majority of whom likely came from urban English contexts.

Diet of late childhood and early adolescence is reflected in the dentine of three individuals; B4, B11 and B21. Of these three individuals both B4 and B21 have $\delta^{15}N$ and $\delta^{13}C$ values that rise from the age of 9 until the end of tooth formation (at 22 years and 13 years respectively). It is possible that this change in diet corresponds with the entering of a different life stage and corresponding change in diet. From the 1830s-1870s nine years old was considered the most usual time for children to begin working (Hopkins, 1994), and isotopic changes may reflect this transition. It is possible that as these individuals began work they were allocated more of the family's higher-quality resources (e.g. meat) in order to maintain their energy for breadwinning (as per Horrell & Oxley, 1999). Alternatively this isotopic pattern may reflect changing nutrient requirements, with children experiencing a negative nitrogen balance in early life causing lower $\delta^{15}N$ values after weaning and prior to 8-9 years (as suggested by Henderson, Lee-Thorp, & Loe, 2014; Schurr, 1997).

Changes to diet with emigration?

All adults known from death registers at SJM immigrated to Milton as adults (Findlay, 2016). Thus their teeth reflect a childhood spent elsewhere, while their later forming tissues (bone and hair) either fully or partially reflect life in New Zealand. All individuals have lower $\delta^{15}N$

values in bone collagen compared with their latest dentinal collagen. This could be interpreted as representing a dietary shift, or perhaps changes to physiological stress levels, in most individuals between tooth and bone formation. However, as observed in King et al. (in press), lower $\delta^{15}N$ values likely reflect lower baseline $\delta^{15}N$ values in the New Zealand context, rather than reduced meat intake. With nineteenth-century baseline values in Britain being approximately 2‰ higher than in New Zealand (King et al., in press a), a shift of less than 2‰ cannot be interpreted as a difference in meat consumption. In fact, most individuals have a shift in $\delta^{15}N$ values of between 0.7 and 1.5‰, which, after baseline adjustment, might suggest higher levels of meat consumption in New Zealand. However, it is also possible that this signal represents a lifetime average composed of dietary inputs in the two countries. Without baselines specific to the place of origin of each individual in the sample, and to Milton, we cannot elucidate this further.

Individuals B4 and B29, whose bone collagen isotopes values lie within the range of their dentinal collagen, may be those for whom emigration involved increased access to meat relative to parts of their childhood. Interestingly, these individuals also have other evidence for wealth that might support this interpretation. As mentioned before, Burial 4 was originally German and acted as the town's doctor, a notable personage in colonial society. It is possible that baseline isotopic values in Germany are different again to those of the UK. Lack of baseline from colonial homelands limits our ability to interpret in this instance, and could be a focus for future work on colonial diet.

Burial 29 is an unidentified female but also has characteristics that set her apart from others in the sample. She is the individual with the tallest stature in the sample, has rib trauma which may be associated with corsetry, and is associated with these best quality and most ornate iron coffin furniture in the cemetery (Petchey, pers comm). These lines of evidence suggest she may have been one of the richer colonists, perhaps coming from an affluent family background.

Evidence for physiological stress:

There are individuals in the sample who have periods in childhood where δ^{15}N values rise but without a corresponding rise in δ^{13}C values, a pattern identified by Beaumont & Montgomery (2016) as evidence for severe nutritional stress. For example, the previously discussed unusual early life isotopic trajectory of B29 may be a result of stress rather than diet. Additionally, there are δ^{15}N value increases without correlated increases in δ^{13}C values, for example the first two points of B4's isotopic profile and for B11 between 4.5-7.5 years of age. It is possible that these times are periods of stress. We note, however, that these spikes in δ^{15}N values are of several years duration, and we question how likely it is that individuals would survive periods of this kind of prolonged stress. If these are childhood stress periods then the move to New Zealand, for these individuals at least, may have involved leaving stressful conditions at home, and improvement of experience in the colony. Another possibility is that these changes are related to the reduction of a nitrogen deficit after growth. During periods of growth the body is in positive nitrogen balance, as more nitrogen is used to form tissues than is excreted, thus nitrogen fractionation is reduced (e.g. Henderson et al., 2014; Waters-Rist & Katzenburg, 2010). Growth has generally been shown to have minimal impact on isotopic values (as per Waters-Rist & Katzenburg, 2010), but it is possible that B4's δ^{15}N value increase between 8-10 years, and B11's between 4.5-7.5 years of age are related to changes in growth rate.

Two individuals also have potential evidence for stress near the end of their lives, with hair δ^{15}N and δ^{13}C values that are raised relative to bone values. For Burial 21 this is a low-magnitude change of 0.6‰, while for B23 it is a change of around 1.5‰. This may be simply evidence of normal dietary oscillation, or a slight change in diet close to time of death. B21 is a known individual whose death registration states his cause of death as pneumonic phthisis haemorrhage, a Victorian diagnosis where phthisis refers to the wasting form of tuberculosis (Olysson, 1836). Family records show that this wasting meant that B21 was unable to work for around six months prior to his death. It is possible that the isotopic changes visible in hair might be related to a slight dietary change associated with a convalescent diet, for example increased reliance on energy-rich foods like beef tea (Snoddy et al., early view). Less likely, acute wasting associated with his tuberculosis caused a rise in δ^{15}N values as the body began to consume its own tissues to make up for energy deficits (Fuller et al., 2005; Mekota et al., 2006; Reitsema, 2013). However usually weight-loss catabolism involves the breakdown of lipid stores, which have more negative $\delta^{13}C$ values, so we would expect isotopic signs of wasting to involve negative co-variance of $\delta^{13}C$ and $\delta^{15}N$ values which is not the case here.

B23 has hair values that are notably higher than their bone collagen values, however they are an unidentified individual with extremely poor bone preservation. It is therefore more difficult to interpret this as evidence for stress at the end of life.

The benefits of combining isotopic results with the historical record:

This study highlights the benefits of historic period bioarchaeological research in general, and isotopic studies in particular. The isotopic results presented here give insight into the personal stories of Milton's first European settlers. They highlight the different experiences each of them had in childhood, from variable weaning behavior to some boys perhaps moving to a more meat-rich diet as they entered the workforce. We tentatively interpret some bone isotope values as indicating equal or higher meat-intake in the New Zealand diet relative to home conditions. This lends some credence to the idyllic image of colonial New Zealand projected by New Zealand company propaganda (New Zealand Company 1841; Vogel 1875). The image of a meat-rich utopia was almost certainly exaggerated, however, and some of the New Zealand meat was likely to have been local wild resources rather than the farmed meat settlers were hoping for (King et al., in press). However, people did perhaps improve their circumstances by moving.

Differences in the isotopic profiles of individuals highlight potential differences in lifestyle both during childhood and in the New Zealand colony. For example, B29 in particular stands out as an individual who was potentially weaned early, had high $\delta^{15}N$ values during childhood and retained a high-level of meat consumption in the colony. This perhaps indicates that her early-life wealth was retained in New Zealand, and allows us to question the concept of egalitarian New Zealand, where the working man could escape the class systems of home (Beattie & Stenhouse, 2007; Fairburn, 1989). Conversely historical information can help us to interpret our isotopic results, particularly because we have individuals of known identity within the sample. Rural dietary patterns, for example, may be responsible for B6's early-life oscillations in diet, while unusual hair $\delta^{15}N$ and $\delta^{13}C$ values in B21 may relate to dietary changes associated with illness. These interpretations would be hard to make with isotopic evidence alone, particularly because we lack isotopic baselines for many colonial and ‘home’ contexts, which limits our interpretive ability.

Conclusion

This study focuses on recreating individual stories using multiple tissues to trace dietary change through the life history of an individual. This approach gives insights into the everyday experiences of colonists, and is particularly useful for those segments of society that the written records tend to leave out (for example rural communities). We show that all individuals in our sample had non-local origins. However, most individuals do not have discernable changes to diet associated with emigration to New Zealand. We propose that there were potential differences in access to meat reflecting socio-economic differences in the supposedly egalitarian new colony. We highlight how serial sampling of tissues that grow at known rates can show potential seasonal variation in diets (e.g. B6), or small-scale dietary shifts that may be associated with care during times of illness (e.g. B21). This biological evidence for the everyday experience of colonists adds a new dimension to colonial narratives. By considering the historical record alongside histories gleaned from the skeletal remains of settlers we may gain increased understanding of this pivotal period in New Zealand history.

Acknowledgements

This work was funded by a Marsden Fast-Start Grant (17-UOO-149) awarded to CK. Excavation was funded by a Grant-in-Aid from the Department of Anatomy, University of Otago. We are grateful to the excavation team - staff and students from the University of Otago, Wayne Stevenson who donated both his time and use of his digger, Kath Croy our ‘camp mum’, and Grant Love (the farmer) for the use of his haybarn, water supply and access to his land. PR and JZ would like to thank the Max Planck Society for funding.

The TP60 group who instigated the work at St. Johns Cemetery and provided a vast amount of background research are Robert Findlay, Kath Croy, Isobel Michelle, Mary-Anne Miller and

Rev. Vivienne Galletly. Bishop Kelvin Wright supported the project wholeheartedly, and provided his permission for the excavation to be undertaken. Megan Callaghan, the Health Protection Officer at Public Health South guided us through the disinterment licence process. Rachel Wesley provided Maori cultural guidance, and participated in the excavation. Richard Walter and Phil Latham of the Department of Archaeology & Anthropology provided much of the excavation and field equipment. We are also grateful to Steve Robertson and Beth Upex for their help in the laboratories at Durham University.

Thanks also go to the two anonymous reviewers, whose thoughtful comments were much appreciated and have significantly improved the manuscript.

Data Availability

The data supporting the findings of this study are available within the article and/or its supplementary materials.

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Figure Legends:

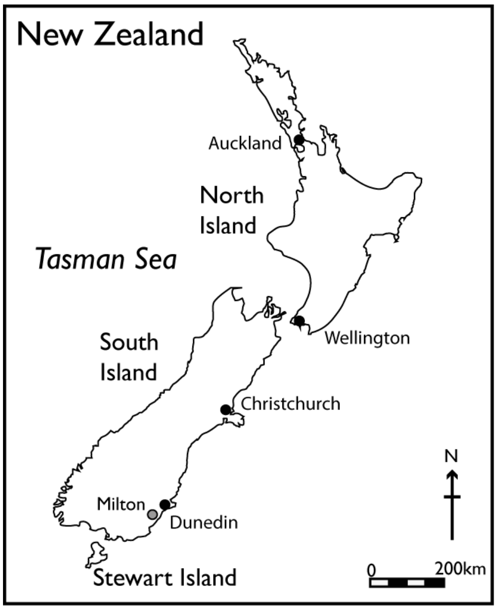

Figure 1: Map of New Zealand showing the location of the study site, St John's in Milton (grey circle)

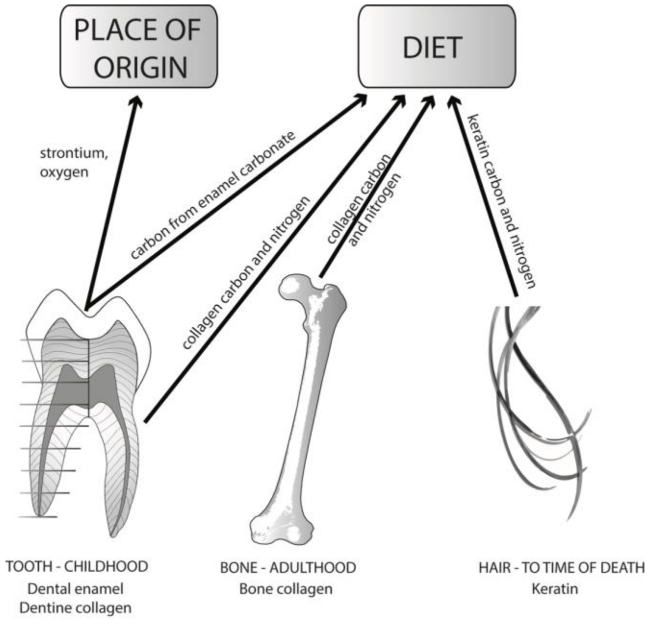

Figure 2: Samples used in this study and the corresponding isotope system employed to reconstruct life history.

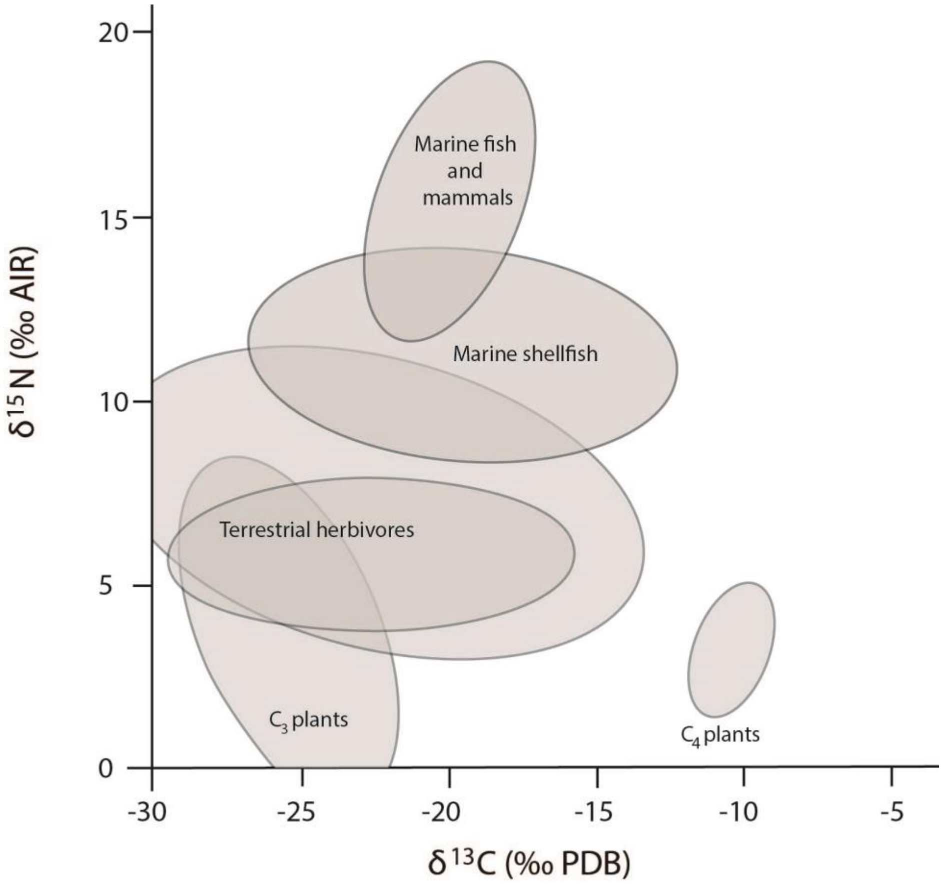

Figure 3: Expected $\delta^{13}C$ and $\delta^{15}N$ values of food sources present in New Zealand, compiled from modern foodweb values (Supplementary Table 1), corrected for changes in atmospheric carbon (Francey et al., 1999).

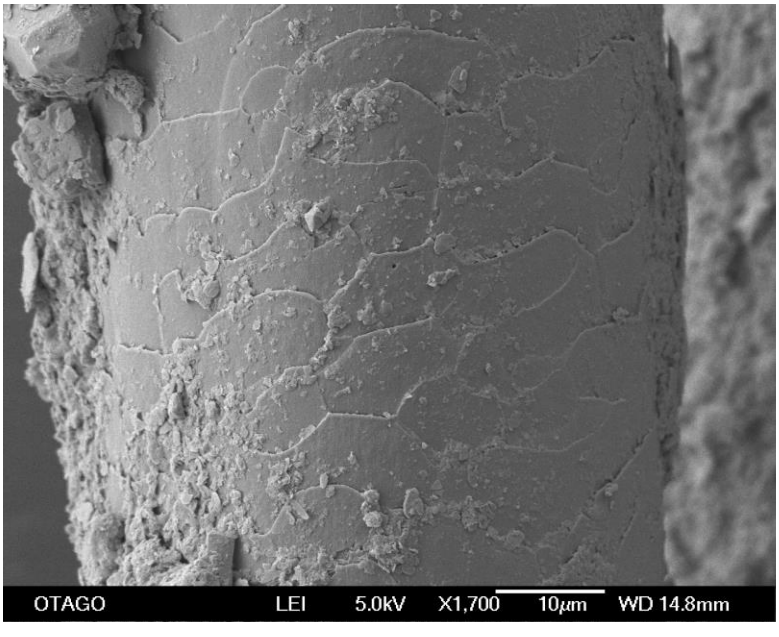

Figure 4: Example SEM image of hair with intact cuticle (from SJM B23).

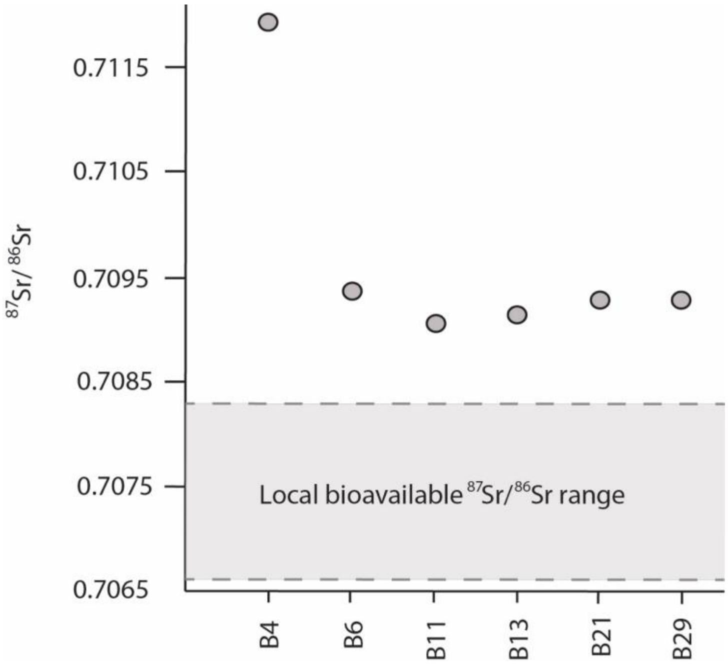

Figure 5: All adult $^{87}Sr/^{86}Sr$ ratios from SJM, plotted with reference to local Milton baseline values from Duxfield et al. (in press). Note that analytical error on all sample values is within symbol area.

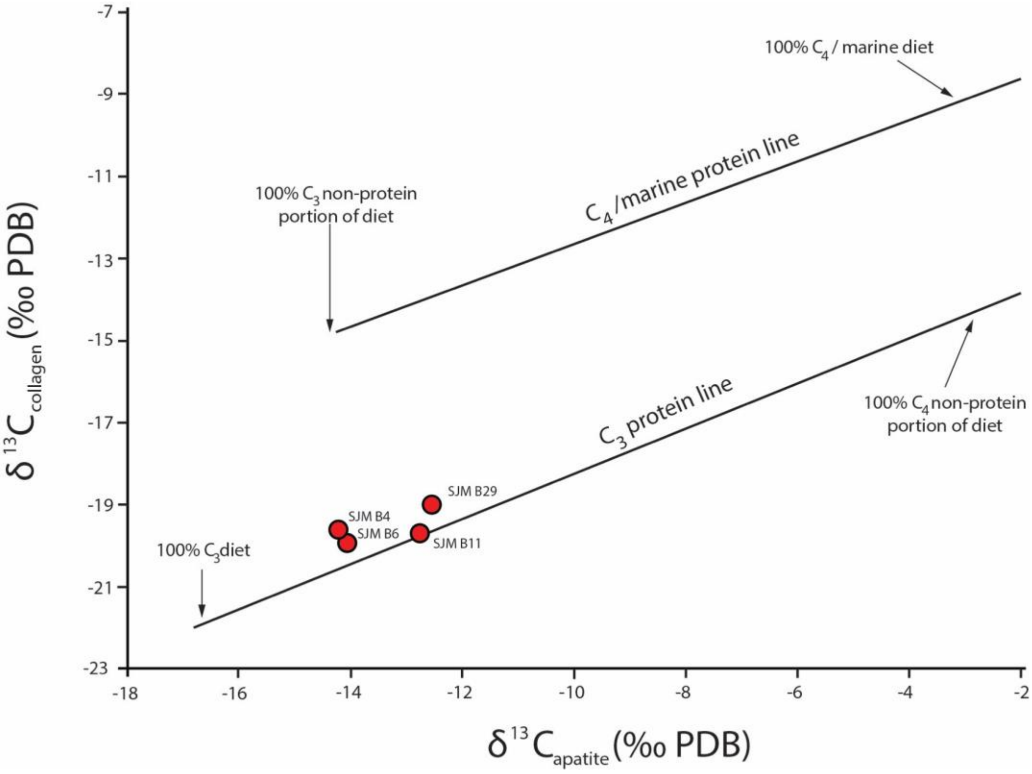

Figure 6: Results of enamel carbonate isotope analysis ($\delta^{13}C_{carb}$) for the selected SJM adults. Note that collagen values used are average values from increments of the lower crown.

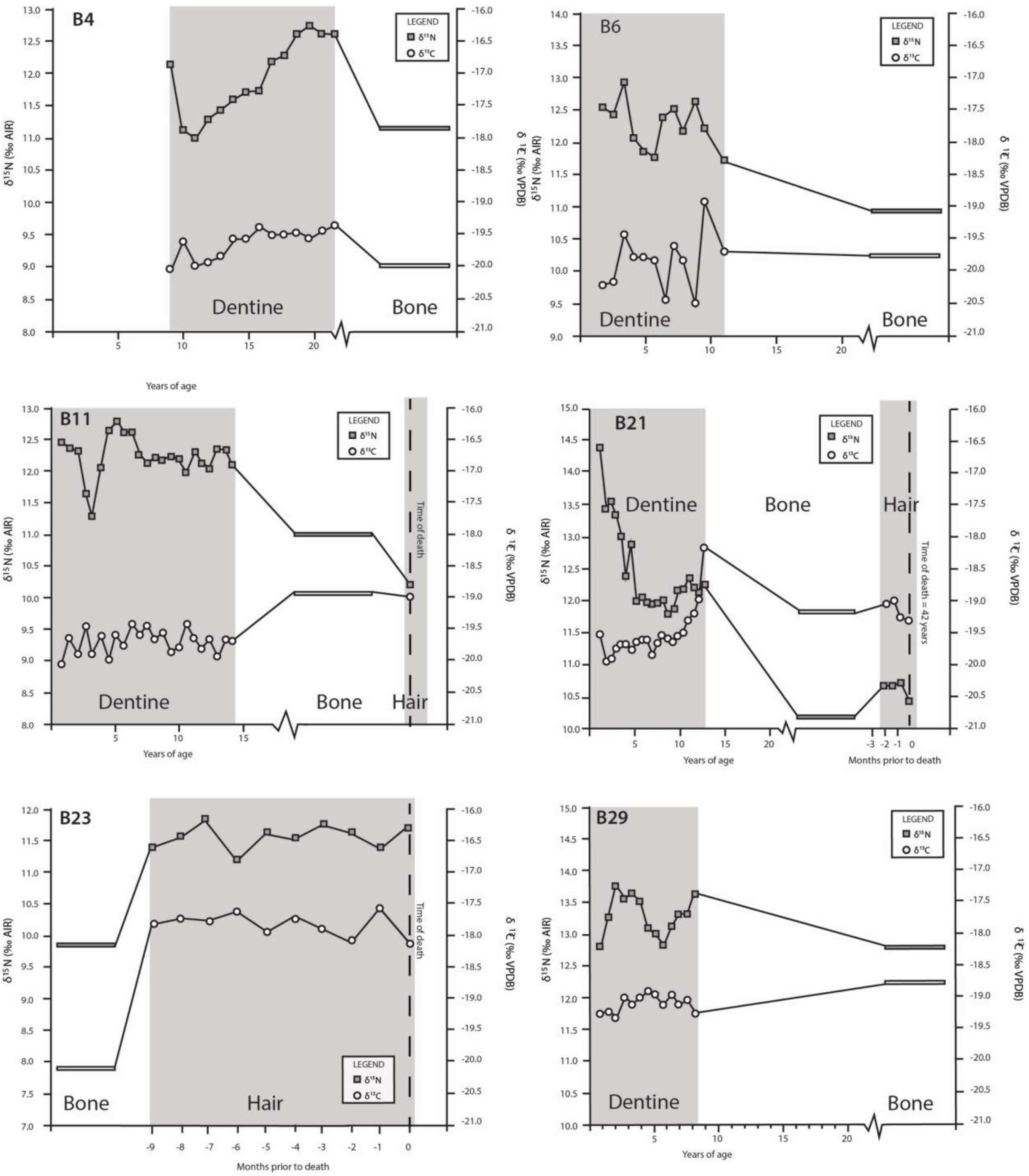

Figure 7: Individual isotopic profiles combining tooth, bone and hair $\delta^{13}C$ and $\delta^{15}N$ values. Bone values broadly represent average adult diet and thus are plotted relatively arbitrarily as > 20 years. Note that hair values have been corrected for the established offsets (approximately +1.4‰ $\delta^{13}C$, +2‰ $\delta^{15}N$) between hair and collagen (Caut, Angulo, & Courchamp, 2009; Drucker, Bridault, Hobson, Szumae, & Hervé, 2008).

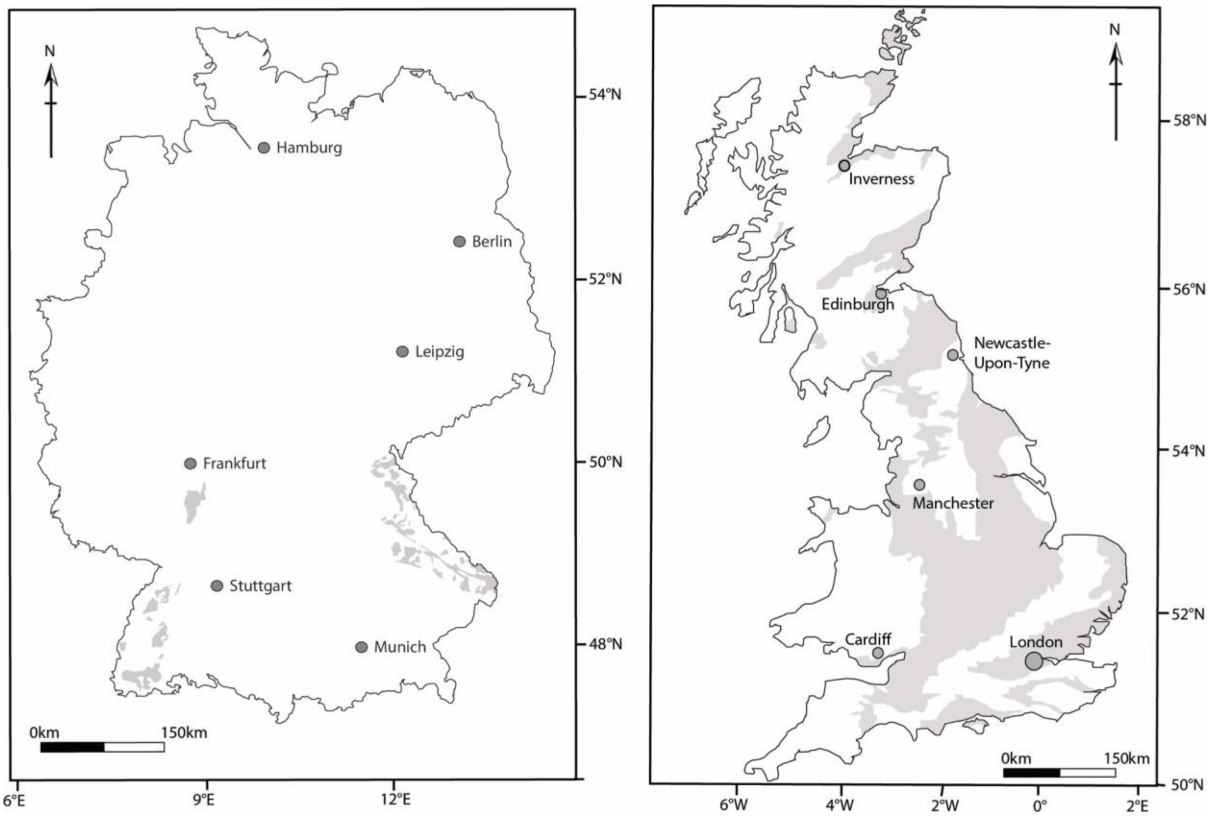

Figure 8: Showing in grey the possible areas of origin in Southern Germany for B4 (Left; adapted from Zitzmann and the UK for other SJM individuals (Right; from Snoddy et al. (2020)

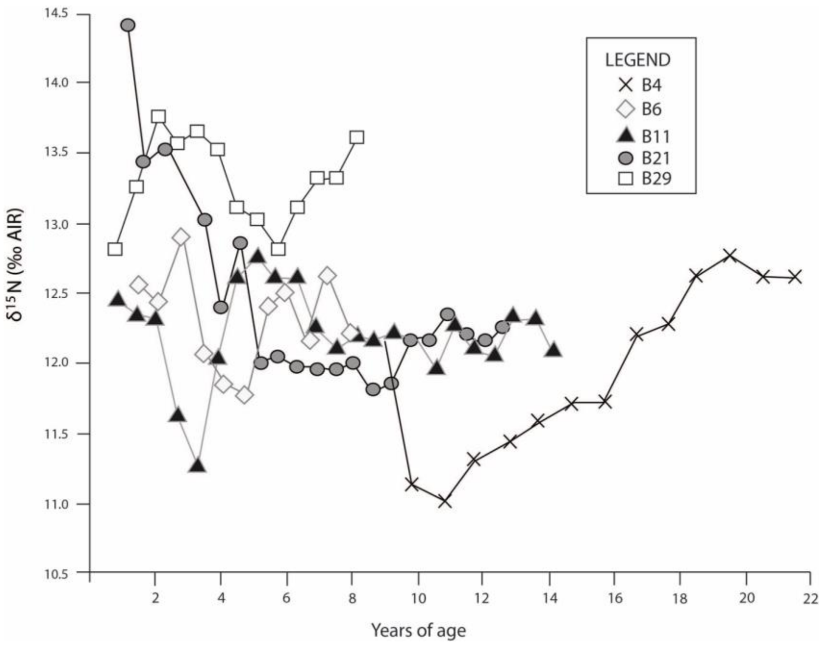

Figure 9: Stable nitrogen isotope results for all individuals with analyzed dentition.

Supplementary Table 1: Baseline foodweb data (from modern and archaeological sources) used in this study.

species	group	tissue type	d13C	fossil fuels correction +0.8 (if modern samples)	bone - flesh correction (if flesh samples) + 3.7	d15N	bone-flesh correction (-1.7 if flesh)	source
kumara (*Ipomoea batatas*)	C3 plant	plant	-26.8	-26	-26	3.8	3.8	Leach et al. (2003)
kumara (*Ipomoea batatas*)	C3 plant	plant	-26.2	-25.4	-25.4	6.4	6.4	Leach et al. (2003)
kumara (*Ipomoea batatas*)	C3 plant	plant	-26.2	-25.4	-25.4	1.2	1.2	Leach et al. (2003)
kumara (*Ipomoea batatas*)	C3 plant	plant	-25.9	-25.1	-25.1	4.6	4.6	Leach et al. (2003)
tī kouka (*Cordyline australis*)	C3 plant	plant	-26.1	-25.3	-25.3	3.7	3.7	Leach et al. (2003)
standard C3 plant	C3 plant	plant	-25.6	-24.8	-24.8	4.3	4.3	Leach et al. (2003)
potato (*Solanum tuberosum*)	C3 plant	plant	-24.5	-23.7	-23.7	3.4	3.4	Rogers (2008)
potato (*Solanum tuberosum*)	C3 plant	plant	-27	-26.2	-26.2	3.4	3.4	Rogers (2008)
pumpkin (*Curcurbita spp*)	C3 plant	plant	-24.7	-23.9	-23.9	2.2	2.2	Rogers (2008)
pumpkin (*Curcurbita spp*)	C3 plant	plant	-23.8	-23	-23	2.2	2.2	Rogers (2008)
peas (*Pisum sativum*)	C3 plant	plant	-25.7	-24.9	-24.9	3	3	Rogers (2008)
peas (*Pisum sativum*)	C3 plant	plant	-28.1	-27.3	-27.3	1.5	1.5	Rogers (2008)
Tuna – longfinned eel (*Anguilla dieffenbachia*)	freshwater fish and birds	muscle	-25.3	-24.5	-20.8	6.7	5	Hicks (1997)
Tuna – longfinned eel (*Anguilla dieffenbachia*)	freshwater fish and birds	muscle	-25.2	-24.4	-20.7	8.4	6.7	Hicks (1997)
Tuna – longfinned eel (*Anguilla dieffenbachia*)	freshwater fish and birds	muscle	-25.6	-24.8	-21.1	9.4	7.7	Hicks (1997)
Tuna – shortfinned eel (*Anguilla australis*)	freshwater fish and birds	muscle	-24.4	-23.6	-19.9	6.1	4.4	Hicks (1997)

Tuna – shortfinned eel (*Anguilla australis*)	freshwater fish and birds	muscle	-23.9	-23.1	-19.4	8.6	6.9	Hicks (1997)
Tuna – shortfinned eel (*Anguilla australis*)	freshwater fish and birds	muscle	-25.2	-24.4	-20.7	8.9	7.2	Hicks (1997)
banded kokopu (*Galaxias fasciatus*)	freshwater fish and birds	muscle	-24.6	-23.8	-20.1	5	3.3	Hicks (1997)
banded kokopu (*Galaxias fasciatus*)	freshwater fish and birds	muscle	-26.1	-25.3	-21.6	6.9	5.2	Hicks (1997)
Crans bully (*Gobiomorphus breviceps*)	freshwater fish and birds	muscle	-25.6	-24.8	-21.1	7.6	5.9	Hicks (1997)
Crans bully (*Gobiomorphus breviceps*)	freshwater fish and birds	muscle	-24.7	-23.9	-20.2	8.6	6.9	Hicks (1997)
redfinned bully (*Gobiomorphus huttoni*)	freshwater fish and birds	muscle	-25.6	-24.8	-21.1	7.6	5.9	Hicks (1997)
redfinned bully (*Gobiomorphus huttoni*)	freshwater fish and birds	muscle	-24.7	-23.9	-20.2	8.6	6.9	Hicks (1997)
koura – crayfish (*Paranephrops planifrons*)	freshwater fish and birds	muscle	-24.5	-23.7	-20	4.5	2.8	Hicks (1997)
koura – crayfish (*Paranephrops planifrons*)	freshwater fish and birds	muscle	-24.5	-23.7	-20	6.2	4.5	Hicks (1997)
koura – crayfish (*Paranephrops planifrons*)	freshwater fish and birds	muscle	-24.4	-23.6	-19.9	7.8	6.1	Hicks (1997)
koura – crayfish (*Paranephrops planifrons*)	freshwater fish and birds	bone	-24	-23.2	-23.2	5.7	7.4	Leach et al. (2003)
Inanga – whitebait (*Galaxias maculatus*)	freshwater fish and birds	bone	-19.5	-18.7	-18.7	8.8	10.5	Leach et al. (2003)
Watersnail (*Latia spp)*	freshwater fish and birds	muscle	-24.1	-23.3	-19.6	7.9	6.2	Hicks (1997)
Watersnail (*Latia spp)*	freshwater fish and birds	muscle	-23.4	-22.6	-18.9	5.8	4.1	Hicks (1997)

mudsnail (*Potamopyrgus spp)*	freshwater fish and birds	muscle	-15.9	-15.1	-11.4	4.3	2.6	Hicks (1997)
mudsnail (*Potamopyrgus spp)*	freshwater fish and birds	muscle	-16.1	-15.3	-11.6	5.4	3.7	Hicks (1997)
mudsnail (*Potamopyrgus spp)*	freshwater fish and birds	muscle	-18.4	-17.6	-13.9	4.5	2.8	Hicks (1997)
hapuku – groper (*Polyprion oxygeneios*)	marine protein	bone	-18	-17.2	-17.2	15.9	15.9	Leach et al. (2003)
pohuiakaroa - sea perch (*Helicolenus percoides*)	marine protein	bone	-15.9	-15.1	-15.1	14	14	Leach et al. (2003)
pohuiakaroa - sea perch (*Helicolenus percoides*)	marine protein	bone	-16.2	-15.4	-15.4	15.8	15.8	Leach et al. (2003)
terakihi (*Nemadactylus macropterus*)	marine protein	bone	-15.6	-14.8	-14.8	13.7	13.7	Leach et al. (2003)
Nihorota - orange roughy (*Hoplostethus atlanticus*)	marine protein	bone	-17.4	-16.6	-16.6	13.9	13.9	Leach et al. (2003)
Nihorota - orange roughy (*Hoplostethus atlanticus*)	marine protein	bone	-16.4	-15.6	-15.6	14.3	14.3	Leach et al. (2003)
blue moki (*Latridopsis ciliaris*)	marine protein	bone	-15.9	-15.1	-15.1	12.4	12.4	Leach et al. (2003)
hokarari – ling (*Genypterus blacodes*)	marine protein	bone	-15.1	-14.3	-14.3	16.4	16.4	Leach et al. (2003)
tāmure – snapper (*Pagrus auratus*)	marine protein	bone	-18	-17.2	-17.2	14	14	Leach et al. (2003)
tāmure – snapper (*Pagrus auratus*)	marine protein	bone	-15.3	-14.5	-14.5	13.7	13.7	Leach et al. (2003)
pakirikiri - spotty (*Notolabrus celidotus*)	marine protein	bone	-16.5	-15.7	-15.7	14.4	14.4	Leach et al. (2003)
wheketere – squid (*Nototodarus spp*)	marine protein	bone	-18.9	-18.1	-18.1	11.7	11.7	Leach et al. (2003)
hoka - red cod (*Pseudophycis bachus*)	marine protein	bone	-18.4	-17.6	-17.6	13.8	13.8	Leach et al. (2003)
kuparu - john dory (*Zeus faber*)	marine protein	bone	-17.5	-16.7	-16.7	15.4	15.4	Leach et al. (2003)
puwhaiau - red gurnard (*Chelidonichthys kumu*)	marine protein	bone	-18.1	-17.3	-17.3	12	12	Leach et al. (2003)
Raawaru (*Parapercis colias*)	marine protein	bone	-18	-17.2	-17.2	11.3	11.3	Leach et al. (2003)
pātiki - lemon sole (*Pelotretis flavilatus*)	marine protein	bone	-17.9	-17.1	-17.1	11	11	Leach et al. (2003)
pātiki - lemon sole (*Pelotretis flavilatus*)	marine protein	bone	-17.6	-16.8	-16.8	12.2	12.2	Leach et al. (2003)
hoki (*Macruronus novaezelandiae*)	marine protein	bone	-16.8	-16	-16	13.4	13.4	Leach et al. (2003)
tio paruparu – oyster (*Tiostrea chilensis)*	marine shell	muscle	-20.1	-19.3	-15.6	9.8	8.1	Leach et al. (2003)

tio paruparu – oyster (*Tiostrea chilensis)*	marine shell	muscle	-18.1	-17.3	-13.6	10.1	8.4	Leach et al. (2003)
tuangi - clam	marine shell	muscle	-16.1	-15.3	-11.6	9.4	7.7	Leach et al. (2003)
tuangi - clam	marine shell	muscle	-16.5	-15.7	-12	8.8	7.1	Leach et al. (2003)
tuangi - clam	marine shell	muscle	-18.1	-17.3	-13.6	7.9	6.2	Leach et al. (2003)
tuangi - clam	marine shell	muscle	-16	-15.2	-11.5	10.7	9	Leach et al. (2003)
limpet sp.	marine shell	muscle	-17.7	-16.9	-13.2	11.9	10.2	Leach et al. (2003)
kuku - green mussel (*Perna canaliculus*)	marine shell	muscle	-17.6	-16.8	-13.1	7.6	5.9	Leach et al. (2003)
tupa – scallop (*Pecten novaezealandiae*)	marine shell	muscle	-16.7	-15.9	-12.2	10.3	8.6	Leach et al. (2003)
tuatua (*Paphies subtriangulata*)	marine shell	muscle	-16.4	-15.6	-11.9	9	7.3	Leach et al. (2003)
tuatua (*Paphies subtriangulata*)	marine shell	muscle	-15.5	-14.7	-11	8.8	7.1	Leach et al. (2003)
kina - sea urchin (*Evechinus chloroticus*)	marine shell	muscle	-17.7	-16.9	-13.2	9.6	7.9	Leach et al. (2003)
cow (*Bos taurus*)	terrestrial herbivore	muscle	-26.32	-25.52	-21.82	5.8	4.1	Heaton et al. (2008)
cow (*Bos taurus*)	terrestrial herbivore	muscle	-22	-21.2	-17.50	5.5	3.8	Bong et al. (2010)
cow (*Bos taurus*)	terrestrial herbivore	muscle	-26	-25.2	-21.50	5	3.3	Bong et al. (2010)
cow (*Bos taurus*)	terrestrial herbivore	muscle	-21.7	-20.9	-17.20	6	4.3	Bong et al. (2010)
cow (*Bos taurus*)	terrestrial herbivore	muscle	-27	-26.2	-22.5	4.5	2.8	Bong et al. (2010)
cow (*Bos taurus*)	terrestrial herbivore	muscle	-23	-22.2	-18.5	6.7	5	Bong et al. (2010)
cow (*Bos taurus*)	terrestrial herbivore	muscle	-25.8	-25	-21.3	5.3	3.6	Horacek and Min (2010)
cow (*Bos taurus*)	terrestrial herbivore	muscle	-27.1	-26.3	-22.6	7.7	6	Horacek and Min (2010)
chicken (*Gallus domesticus*)	terrestrial herbivore	egg	-20.5	-19.7	-19.7	5.3	5.3	Rogers et al. (2015)
chicken (*Gallus domesticus*)	terrestrial herbivore	egg	-19.8	-19	-19	5.7	5.7	Rogers et al. (2015)
chicken (*Gallus domesticus*)	terrestrial herbivore	egg	-20.5	-19.7	-19.7	5.8	5.8	Rogers et al. (2015)
chicken (*Gallus domesticus*)	terrestrial herbivore	egg	-20.7	-19.9	-19.9	6.7	6.7	Rogers et al. (2015)
maize (*Zea mays*)	C4 plant	plant	-11.8	-11	-11	3.3	3.3	Bahar et al. (2005)
maize (*Zea mays*)	C4 plant	plant	-10.4	-9.6	-9.6	3.4	3.4	Rogers (2008)
maize (*Zea mays*)	C4 plant	plant	-10.9	-10.1	-10.1	3	3	Rogers (2008)
maize (*Zea mays*)	C4 plant	plant	-11.4	-10.6	-10.6	3.6	3.6	DeNiro and Hastorf (1985)

maize (*Zea mays*)	C4 plant	plant	-11.6	-10.8	-10.8	2.9	2.9	DeNiro and Hastorf (1985)
maize (*Zea mays*)	C4 plant	plant	-12.2	-11.4	-11.4	2.1	2.1	DeNiro and Hastorf (1985)
maize (*Zea mays*)	C4 plant	plant	-10.3	-9.5	-9.5	3	3	DeNiro and Hastorf (1985)
maize (*Zea mays*)	C4 plant	plant	-11.4	-10.6	-10.6	2.5	2.5	DeNiro and Hastorf (1985)
maize (*Zea mays*)	C4 plant	plant	-11.3	-10.5	-10.5	2.3	2.3	DeNiro and Hastorf (1985)
maize (*Zea mays*)	C4 plant	plant	-10.9	-10.1	-10.1	4.7	4.7	DeNiro and Hastorf (1985)
maize (*Zea mays*)	C4 plant	plant	-11.2	-10.4	-10.4	3.9	3.9	DeNiro and Hastorf (1985)

Supplementary Table 2: All collagen results

Individual	Sample Type	Section	δ^{13}C (‰ PDB)	δ^{15}N (‰ AIR)	%C	%N	C:N	Age represented by increment
SJM B4	Mand. LM3 dentinal collagen	1	-20.0	12.1	42.2	15.4	3.2	9.0
		2	-19.6	11.1	43.8	16.0	3.2	9.9
		3	-20.0	11.0	43.6	16.2	3.1	10.9
		4	-19.9	11.3	42.6	15.9	3.1	11.9
		5	-19.8	11.4	-19.7	15.9	3.2	12.8
		6	-19.6	11.6	43.4	15.6	3.2	13.8
		7	-19.6	11.7	41.9	15.4	3.2	14.8
		8	-19.4	11.7	42.9	15.5	3.2	15.7
		9	-19.5	12.2	42.0	15.5	3.2	16.7
		10	-19.5	12.3	42.4	15.4	3.2	17.7
		11	-19.5	12.6	43.1	15.6	3.2	18.6
		12	-19.6	12.7	41.7	15.4	3.2	19.6
		13	-19.4	12.6	41.8	15.2	3.2	20.6
		14	-19.4	12.6	42.6	15.4	3.2	21.5
	Bone collagen	bulk sample	-20.0	11.1	30.2	10.6	3.3	adulthood
SJM B6	L Max. I1 dentinal collagen	1	no yield					0.9
		2	-20.23	12.54	41.49	14.93	3.2	1.6
		3	-20.18	12.43	40.81	15.13	3.1	**2.2**
		4	-19.42	12.91	43.31	15.13	3.3	2.9
		5	-19.79	12.07	40.83	15.08	3.16	3.5
		6	-19.77	11.85	43.06	14.45	-19.77	4.1
		7	-19.84	11.76	42.54	14.35	-19.84	4.8
		8	-20.46	12.39	41.15	14.54	-20.46	5.4
		9	-19.61	12.53	42.16	14.22	-19.61	6.1

		10	-19.87	12.16	42.59	14.09	-19.87	6.7
		11	-20.51	12.65	40.47	12.98	-20.51	7.4
		12	-18.93	12.20	41.79	13.66	-18.93	8.0
		13	no yield					8.6
		14	-19.70	11.72	34.75	11.47	-19.70	9.3
	bone collagen	bulk sample	-19.79	10.96	30.00	10.10	3.5	adulthood
SJM B11	R Max. canine dentinal collagen	1	-20.1	12.4	41.41	14.25	3.4	0.9
		2	-19.7	12.4	42.95	15.13	3.3	1.5
		3	-19.9	12.3	41.98	15.08	3.2	2.1
		4	-19.5	11.6	42.32	15.15	3.3	2.7
		5	-19.9	11.3	43.08	15.22	3.3	3.3
		6	-19.6	12.0	41.74	15.01	3.2	3.9
		7	-20.0	12.6	41.76	14.90	3.3	4.5
		8	-19.6	12.8	42.18	14.91	3.3	5.1
		9	-19.8	12.6	41.49	15.01	3.2	5.7
		10	-19.4	12.6	42.67	15.27	3.3	6.3
		11	-19.6	12.2	42.05	15.22	3.2	6.9
		12	-19.5	12.1	42.36	15.07	3.3	7.6
		13	-19.7	12.2	42.18	15.27	3.2	8.2
		14	-19.6	12.2	42.66	15.13	3.3	8.8
		15	-19.9	12.2	41.12	14.83	3.2	9.4
		16	-19.8	12.2	42.39	15.06	3.3	10.0
		17	-19.4	12.0	42.68	15.00	3.3	10.6
		18	-19.7	12.3	43.26	15.03	3.4	11.2
		19	-19.8	12.1	43.07	15.13	3.3	11.8
		20	-19.7	12.0	42.76	15.07	3.3	12.4
		21	-20.0	12.3	42.89	15.02	3.3	13.0
		22	-19.7	12.3	43.01	14.89	3.4	13.6

		23	-19.7	12.1	42.94	14.79	3.4	14.2
	bone collagen	bulk sample	-19.0	11.0	39.8	13.5	3.5	adulthood
	hair keratin	1	-19.0	10.2	40.24	12.63	3.7	close to time of death
SJM B21	L Mand. canine dentinal collagen	1	-19.53	14.39	43.31	15.43	3.3	1.2
		2	-19.96	13.43	43.03	15.33	3.3	1.8
		3	-19.92	13.56	43.11	15.55	3.2	2.3
		4	-19.76	13.34	43.11	15.48	3.2	2.9
		5	-19.67	13.02	43.28	15.44	3.3	3.5
		6	-19.69	12.38	42.79	15.38	3.2	4.1
		7	-19.78	12.88	43.24	15.4	3.3	4.6
		8	-19.66	11.98	42.86	15.4	3.2	5.2
		9	-19.63	12.06	43.16	15.39	3.3	5.8
		10	-19.61	11.98	42.7	15.2	3.3	6.4
		11	-19.84	11.94	44.22	15.6	3.3	6.9
		12	-19.67	11.95	43.09	15.12	3.3	7.5
		13	-19.56	12.01	42.96	15.18	3.3	8.1
		14	-19.61	11.8	44	15.35	3.3	8.7
		15	-19.66	11.86	43.82	15.37	3.3	9.3
		16	-19.56	12.16	43.15	15.3	3.3	9.8
		17	-19.5	12.19	43.01	15.15	3.3	10.4
		18	-19.31	12.36	42.27	14.95	3.3	11.0
		19	-19.2	12.2	43.12	15.11	3.3	11.6
		20	-18.99	12.14	43.12	15.01	3.3	12.1
		21	-18.17	12.25	43.72	15.14	3.4	12.7
	bone collagen	bulk sample	-19.2	10.2	35.7	12.5	3.3	adulthood
	hair keratin	1	-19.3	10.5	40.19	12.07	3.9	time of death
		2	-19.2	10.7	40.01	12.41	3.8	death - 1 month
		3	-19.0	10.7	42.20	13.57	3.6	death - 2 months

		4	-19.0	10.7	41.89	13.49	3.6	death - 3 months
SJM B23	bone collagen	bulk sample	-20.1	9.9	41.2	15.0	3.2	adulthood
	hair keratin	1	-18.1	11.7	41.89	13.84	3.5	time of death
		2	-17.6	11.3	33.84	11.01	3.6	death - 1 month
		3	-18.1	11.6	37.68	12.62	3.5	death - 2 months
		4	-17.9	11.7	42.07	13.88	3.5	death - 3 months
		5	-17.7	11.5	41.39	13.75	3.5	death - 4 months
		6	-18.0	11.6	41.40	13.85	3.5	death - 5 months
		7	-17.6	11.2	43.80	14.63	3.5	death - 6 months
		8	-17.8	11.8	42.30	14.18	3.5	death - 7 months
		9	-17.7	11.5	36.72	11.98	3.6	death - 8 months
		10	-17.8	11.3	42.15	14.18	3.5	death - 9 months
SJM B29	Mand. I2 dentinal collagen	1	-19.2	12.81	40.1	14.3	3.3	0.90
		2	-19.2	13.26	43.2	15.3	3.3	1.51
		3	-19.3	13.76	42.3	15.1	3.3	2.12
		4	-19.0	13.56	42.2	15.1	3.3	2.73
		5	-19.1	13.64	43.5	15.4	3.3	3.33
		6	-19.0	13.52	42.1	15.1	3.3	3.94
		7	-18.9	13.09	42.3	15.2	3.3	4.55
		8	-19.0	13.01	42.8	15.3	3.3	5.16
		9	-19.1	12.83	42.7	15.2	3.3	5.77
		10	-19.0	13.12	42.3	15.2	3.2	6.37
		11	-19.1	13.32	42.7	15.1	3.3	6.98
		12	-19.0	13.32	42.0	15.0	3.3	7.59
		13	-19.2	13.62	42.1	14.6	3.4	8.20
	bone collagen	bulk sample	-18.8	12.8	32.5	11.2	3.4	adulthood