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Seeking their fortunes on the Otago goldfields, New Zealand – Constructing isotopic biographies of colonial goldminers

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ABSTRACT

The nineteenth century New Zealand goldfields were a place where people from across the world came together in search of their fortunes. Written accounts of life on the diggings do exist but are of varying veracity and we therefore have little knowledge of the life experiences of those who came seeking gold. Recent excavations in cemeteries associated with the Otago goldrushes, however, are allowing direct reconstruction of lives using biological evidence from the skeletons themselves. In this study we use dietary isotope analysis ($\delta^{13}C$ and $\delta^{15}N$) of tissues which form at different points in the life course of an individual to create 'isotopic biographies' of goldrush-era individuals. In addition to telling the individual stories of these people, we also highlight differences in life experience between members of the European and Chinese communities, evidence for seasonal availability of resources on the goldfields, as well as unusual weaning patterns which potentially link to rural poverty experienced during childhood.

1. Introduction

The Otago goldrushes began in 1861, heralding a time of unprecedented emigration to the fledgling British colony of New Zealand (Forrest 1961; Salmon 1963). The first large goldrush began in June–July 1861 in the township of Tuapeka (later called Lawrence) located in Central Otago, South Island (Fig. 1). From here miners made their way to connected goldfields in Central Otago, with the Dunstan Rush beginning in 1862. Most who came to the goldfields were seeking to improve their fortunes in life, either by making enough money to buy property or set up businesses in New Zealand, or by setting themselves up with enough wealth to live comfortably once they returned to their natal countries (Carpenter 2012). For many, this never came to pass. Death on the goldfields was common (Petchey et al. 2021), and striking large amounts of gold was a relatively infrequent occurrence (Carpenter 2012).

The goldrushes took place against a backdrop of increasing industrialisation in Europe. In the United Kingdom, land enclosure acts had restricted animal grazing, forcing many of those living in rural areas into poverty (Neeson 1993). Burgeoning urban centres were experiencing massive population influxes, resulting in many living in crowded, unsanitary conditions (Engels 1892; Hudson 1992). Disease was rife and food was expensive especially prior to the repealing of the Corn Laws which artificially raised the price of grain (Burnett 1989). Records from the period suggest that most of the poor could rarely afford meat, and subsistence was heavily based on the staples of bread and potatoes (Kay 1832; Burnett 1989). For many, emigration offered the hope of a better life, where the conditions of the industrial revolution in Europe could be escaped (Simpson 2012). The discovery of gold in California (1848) provided the impetus many needed to leave (Goodman 1994). These would-be miners became highly mobile individuals, following the subsequent discoveries of gold across the Pacific rim. Many of those who ended up in New Zealand were originally from Europe but had initially left for the California or Victoria (Australian) goldrushes before moving to the goldfields of Central Otago (Carpenter and Fraser 2016; Mountford and Tuffnell 2018).

At the same time, land disputes, internal political upheaval and the Opium Wars were ongoing in China and had forced much of the rural

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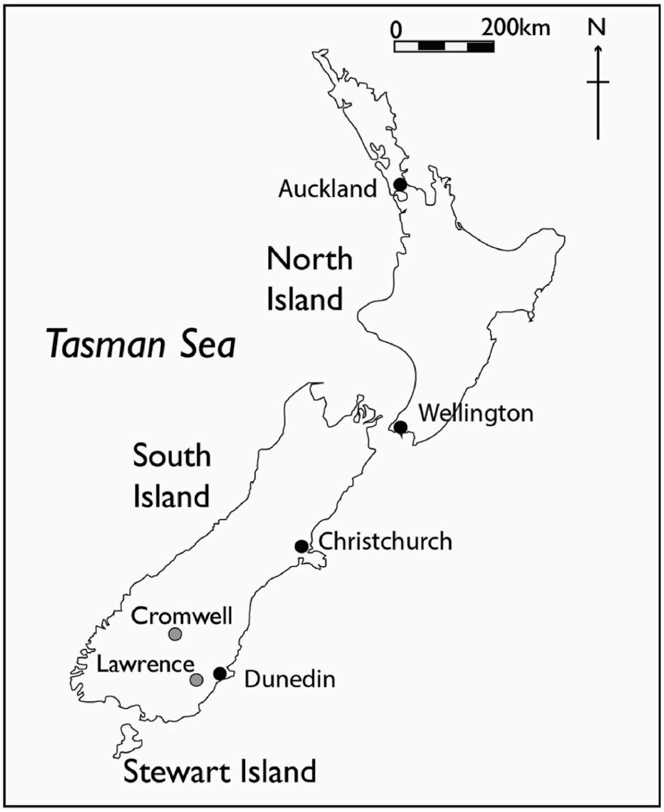

Fig. 1. Location of the two study townships, Lawrence and Cromwell (grey circles), in relation to major New Zealand cities (black circles).

population in Guangdong province into extreme poverty (Mei 1979; Ng 2003). Here too populations were growing, the price of land and food was at a premium and many could not afford to support themselves or their families. Emigration to New Zealand was not advertised to the Chinese in the same way as it was to people in the United Kingdom. However, as a port city, Guangzhou provided an ideal springboard from which fortune-seekers could depart (Ng 1993, 2003). Unlike many of their European contemporaries on the goldfields, most Chinese miners did not intend to remain in New Zealand. The men who travelled to mine often left wives and families in China. They were sojourners, aiming to earn enough to lift themselves out of poverty upon their return (Ng 2003; Reeves 2010).

Historical records give us a broad overview of who the miners on the New Zealand goldfields were. We know, for instance, that Europeans on the goldfields primarily came from Britain and Ireland, but that a large number also came from Germany and Scandinavian countries (Phillips and Hearn 2008). This early rush population was dominated by men who outnumbered women by 2:1 in the 1864 census (Lake Wakatip Mail, 1865), and likely by far more than this at the height of the rush. Historical records also suggest that most of the Chinese miners on New Zealand's goldfields came from poor, rural settings in Guangdong (Mei 1979; Ng 2003), sometimes via the Australian goldfields, like their European counterparts. However, recent mobility isotope and genetic research has highlighted diversity in origins within both the European and Chinese populations at the goldrush settlement of Lawrence or Tuapeka, as it was known (King et al., 2021a,b).

In this study, we build on mobility isotope work previously conducted on individuals from the Tuapeka rush, by collating carbon and nitrogen isotopic records from tissues forming at different life stages. Carbon and nitrogen isotopic analysis can give insight into diet, as well as some aspects of health. Together, therefore, isotopic records from these tissues allow us to explore changes associated with childhood experience (breastfeeding, weaning and other dietary oscillations), dietary shifts upon moving to New Zealand, and end of life diet and/or stress experiences.

Miners came to the goldfields from all walks of life, and while most had poorer backgrounds and lacked the time or inclination for describing their experiences, a few wrote letters and recollections of their time on the diggings (Martin 1861; Walker 1862; Houston 1865). Overwhelmingly, however, these recollections are written by those who experienced success in the initial rushes or were of independent enough means to live when gold was not plentiful. Those who did not prosper on the goldfields, came from lower class backgrounds, or were in marginalised communities (like the Chinese) are less likely to be represented in the historical record. For example, much of what we do know about the Chinese on the goldfields was collated by a Presbyterian missionary (Alexander Don). These records, however, do not begin until 1883, long after the initial influx of Chinese migrants into Otago. Women, in this period, were also relatively marginalised or misrepresented. They are either relegated to the role of silent wives or mothers in accounts, or reported on salaciously as prostitutes or women of ill-character (even in modern commentaries e.g. Eldred-Grigg 2008).

The everyday life experience of those living on the Otago goldfields is therefore largely missing from the historical records. Archaeological evidence goes some way to fill in the gaps, and research on Otago's goldfields has allowed insights into both European and Chinese settlement patterns (Ritchie 1980; Bristow 1995), mining technologies (Petchey 2019), importation practices (Ritchie 1980; Ritchie and Bedford 1983; Petchey and Innanchai 2012), healthcare (Smith and Garland 2012) and diet (Piper 1988; Smith and Garland 2012). Similar archaeological research undertaken on the Australian goldfields is also relevant to the New Zealand cultural context, due to the mobility and shared culture between these areas (Lawrence 2003; Ritchie 2003a; Fleming 2016). Together, archaeological evidence from both Australia and New Zealand tells the story of the adaptability of the miners (Ritchie 2003b; Lawrence and Davies 2015), informs us about retention of their cultural practices or lack thereof (Ritchie 1986; Smith 2003), and allows us to interpret aspects of their lifestyles, including health (Smith and Garland 2012) and gender roles (Lawrence 1999; Prangnell and Quirk 2009).

This archaeological evidence cannot, however, inform us directly about the lived experiences of these people. Instead, evidence from the skeletal remains of those living at the time can be used to give insight into the biological aspects of life experience. Up until the recent undertaking of the Southern Cemeteries Archaeology Project (with which these results are associated), very few bioarchaeological studies of colonial settlers had been undertaken in New Zealand. The initial results from this project's work at the pastoral colonial site of St. John's Milton, however, have shown how biological evidence can inform on origins (King et al. 2020), diet (King et al. 2021), and health (Snoddy et al. 2020, 2021) of both adults (Buckley et al. 2020) and children (King et al. 2022; Kavale Henderson et al. in review) living in colonial New Zealand. This kind of biological evidence in combination with the archaeological evidence has the potential to give us a more nuanced understanding of life on the goldfields.

In this paper we focus on excavations in cemetery sites associated with the first of the major New Zealand goldrushes (Gabriels Gully, Tuapeka, 1861). Already osteological and chemical analysis of individuals from these sites are allowing new insights into the lives of these forgotten goldfields inhabitants (Petchey et al. 2018a,b; King et al. 2021). Here we build on this research by presenting isotopic records of diet from throughout the lifecourse of these individuals.

2. Archaeological context

This study incorporates individuals from two central Otago goldfields townships; Lawrence and Cromwell (Fig. 1). We use two sites from Lawrence; the earlier Ardrossan St cemetery (1861-ca1864) now designated as archaeological site H44/1135, and the later 'Chinese' section of the Gabriel St cemetery (archaeological site H44/1136, burials dating 1864-onwards) (Petchey et al. 2018a,b). These cemetery sites were excavated as part of the Southern Cemeteries Archaeology project over two field seasons in 2018 and 2019, under Archaeological Authority No. 2018/456 issued by Heritage New Zealand and Disinterment Licence No 09/2018 issued by the Ministry of Health. This project was undertaken as a joint community and research project, in collaboration with and/or consultation with the Lawrence Tuapeka Community Board, the Otago-Southland Chinese Association, Te Rūnanga o Ōtakou and local and descendant groups. All individuals were fully excavated, recorded by the research team in laboratory settings at the University of Otago, and were reinterred in the Gabriel's St cemetery in April 2023 as per the wishes of the community.

This study also includes two individuals buried in the Cromwell cemetery who were assessed as part of a rescue in 2017 after council tree-felling works accidently uncovered them. They were recorded in the field during at which time isotopic samples were taken with permission, and the individuals were reburied on site immediately (Petchey et al. 2018a,b).

The Lawrence and Cromwell sites essentially represent a time period encompassing the first rush in Tuapeka, through to the later rushes in Central Otago. Lawrence and Cromwell are connected goldrush contexts as many miners who came to Lawrence for the first rush moved to Cromwell when gold was found in the Clutha River in 1862 (Forrest 1961).

2.1. The Lawrence cemeteries

The Ardrossan St cemetery was the first established in the area, and represents individuals involved in the initial Tuapeka goldrush to the region. In total 25 individuals were found at this site, and excavated as a part of this study. Skeletal preservation at the site, however, was very variable. Most individuals are represented only by teeth and/or hair likely due to acidic ground water flow damaging the integrity of the bones.

The Ardrossan St cemetery was in operation from 1861–ca.1864, and while there are no surviving burial records for this site, it is generally assumed to represent a predominantly European goldmining population (Petchey et al. 2018a,b), a fact corroborated by the typically 'Western European' genetic haplogroups exhibited by all individuals with aDNA preserved from the site (King et al. 2021). Mobility isotope work, however, does highlight the diversity in origins of these people, suggesting that they came from various regions within Europe (King et al. 2021). The inclusion of rice grains in one of the Ardrossan burials (A19) also raises the possibility of at least one individual being Chinese in that burial ground.

The Gabriel St cemetery was established around 1864 and remains in operation to the present day. The largely unmarked 'Chinese' portion of the cemetery was partially excavated during this study (Petchey et al. 2018a,b), revealing 27 grave cuts. Of the 21 excavated, 12 had been historically exhumed during the Chinese repatriations of ancestral remains which occurred in 1883 and 1902, and nine contained human remains. Based on contextual evidence, burials in this area all pre-date the late 1890s (Petchey et al. 2018a,b). No burial records were kept for this part of the cemetery, and it is unknown who may have originally been interred here. The area was designated the "Chinese" section, and although it is possible that others may have been buried there too, including so-called 'paupers' who could not afford plots in the European part of the cemetery, mobility isotope and genetic research conducted here indicates that many excavated individuals have genetic haplogroups and isotopic values that align with those expected for people hailing from Guangdong province, China. All individuals had items of Chinese material culture associated with them, however one individual has a mitochondrial haplogroup that is typically European, and several individuals isotopically fall outside the expected range for Guangdong. This hints that, despite all individuals being culturally Chinese, they did have diverse places of origin (King et al. 2021).

2.2. The Cromwell individuals

The individuals recovered from Cromwell are both male, and their burials likely date to the 1890s. In the field, 'shovelling' was observed on the incisors of one of the individuals (B2), a non-metric trait most common in (but not restricted to) Asian populations (Scott et al. 2016). It is, therefore, possible that at least one of these people was of Chinese ancestry. The period from which the two Cromwell individuals date is well after the initial Dunstan rush in 1862 (Forrest 1961). However, in the following decades mining continued to be the mainstay of the economy at Cromwell, alongside growing industry, and farming.

The individuals from these three contexts likely represent diverse life experiences. Considered together, their reconstructed life stories allow us to build a picture of the transient goldfields populations, including their lives before moving to New Zealand.

3. Materials and methods

3.1. The samples

Teeth that form during the period of breastfeeding and weaning were preferentially sampled (i.e. M1s, incisors, and canines) to give insight into this significant period of development. Bone samples were preferentially taken from elements which turnover quickly (e.g. the rib as per Fahy et al., 2017). However, taphonomic conditions at both Lawrence sites meant that many individuals did not have well-preserved mineralised tissues, and thus sampling was limited by preservation. Of the 34 individuals excavated from Lawrence, only 13 had bones/teeth which could be sampled, and of these only 10 yielded good collagen. Hair, however, was unusually well-preserved, and present in eight of the Lawrence burials (Fig. 2). As hair is forming up until time of death it gives us the opportunity to examine experiences leading up to the end of life, something which is not usually possible in archaeological contexts.

Sex estimation was undertaken using the sexually dimorphic features of the pelvis and cranium (Phenice 1969; Buikstra and Ubelaker 1994) where bone was preserved. However, A24 has been estimated as female due to the length and style of hair and possible presence of a child buried alongside them. This individual did not have good enough skeletal preservation to allow osteological sex estimation. Population affinity was established using mtDNA evidence (when DNA was preserved) or material culture such as preserved queues, clothing or mortuary offerings associated with the burial (as reported in King et al., 2021a,b).

The presumed female in the sample (A24), and the Chinese individuals with queues (long Chinese plaits) had by far the longest hair samples, and therefore have more datapoints associated with them. Both Cromwell individuals yielded well-preserved collagen. However, only one had preserved hair. Full details of the samples taken for analysis are given in Table 1.

3.2. Stable isotope analysis background

In this study we examine carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope data from human dentine collagen, bone collagen and keratin (hair), alongside $\delta^{13}C$ of bioapatite from dental enamel. The sampled tissues each form at different points in an individual's life and together allow us to examine childhood diet (using dentine collagen and bioapatite), average adult diet on the goldfields (using bone collagen), and dietary change in the last months of individuals' lives (using hair).

These isotopic systems have well-established links to both plant types at the base of food chains ($\delta^{13}C$), and the trophic level of resources consumed ($\delta^{15}N$). Used together they can highlight meat consumption, or lack thereof, reliance on different crops, and whether or not marine foods are being consumed. Incremental studies of hair and dentinal collagen have also highlighted that severe nutritional or metabolic stress may alter isotopic ratios (Fuller et al. 2005; Mekota et al. 2006). If stress is severe enough, the body may begin to catabolise its own tissues,

Fig. 2. The exceptional preservation of hair in the study sample. Here, individual G7's hair is shown, styled in a traditional Chinese queue.

leading to further fractionation of nitrogen isotopes and a trophic level rise of 2–5‰ in $\delta^{15}N$ (Fuller et al. 2005; Reitsema 2013), with a corresponding rise or fall in $\delta^{13}C$ depending on which tissue is catabolised to make up the energy deficit. In addition to these processes, other metabolic changes such as pregnancy may cause characteristic changes to isotopic values (Fuller et al. 2004). These changes include spikes in $\delta^{15}N$ values during the first trimester, associated with morning sickness, and gradual decreases in $\delta^{15}N$ values between 0.5 and 1‰ over the course of the pregnancy associated with maternal nitrogen retention.

3.3. Time-resolved vs. bulk isotopic sampling

In this study we use both bulk sampling and serial sampling methods, depending on the tissue analysed. As tissues which form and then do not remodel, both dentine and hair have been sampled in serial sections in this study, providing multiple datapoints which represent different points in the tissues' formation. Dentinal values represent different periods of childhood depending on which tooth has been sampled and how many increments were obtained from the tooth (Beaumont and Montgomery 2015). In general increments represent between 6 months and a year of life, although sampling methods which cross-cut the geometry of tooth formation can 'blur' the time resolution (Tsutaya 2020). Despite this, incremental sampling strategies still allow much greater insight into changing childhood conditions than traditional bulk sampling methods do. In particular changes to $\delta^{15}N$ and $\delta^{13}C$ values during infancy and early childhood can be used to examine when the weaning process occurred, weaning constituting a decrease in trophic level as the child moves from 'consuming' its mother's tissues, to a diet more similar to that of the mother (Millard 2000; Eerkens et al. 2011; Tsutaya and Yoneda 2015).

Hair, on the other hand, is growing until time of death and can give insight into dietary fluctuations close to the end of life, as well as possibly periods of pregnancy, metabolic stress, or starvation before the individual died (Fuller et al. 2004, 2005; Mekota et al. 2006). Since hair grows at an average rate of 1 cm per month, it can be sectioned for incremental analysis (Saitoh et al. 1969) to examine the life of an individual on a month-by-month basis. Multiple studies have shown that hair generally registers changes to diet within 6–12 days (e.g. Nakamura et al. 1982), however it takes the hair closer to 3 months to reach equilibrium with these new dietary values, during which values will fluctuate slightly (Huelsemann et al. 2009). Hair will therefore reflect dietary changes quickly but will not necessarily allow us to accurately assess the magnitude of changes to diet if those changes are short-lived (Williams and Katzenberg, 2012).

We plot incremental results from dentine and hair alongside average adult dietary values, obtained from bulk bone collagen samples. This allows us to look more generally at changes to diet between a childhood spent overseas and adulthood in New Zealand, and between the average adult diet and diet leading up to death.

3.4. Assessing dietary components

Collagen $\delta^{15}N$ and $\delta^{13}C$ values from collagen allow us to see broad differences in diet between individuals. However the $\delta^{13}C$ offset between diet and collagen varies based on whole diet composition (Froehle et al. 2010), so it is difficult to use these values to directly extrapolate resources used. In this scenario $\delta^{13}C$ carbonate values from dental enamel bioapatite can be useful as a proxy for whole diet (i.e., all the macronutrients—carbohydrates, lipids, and proteins). Bivariate regression models using enamel carbonate and collagen $\delta^{13}C$ values can therefore allow more insight into the contributions of C_3 and C_4 protein, as well as marine protein in the diet (Froehle et al. 2010). In this study, because movement between subsistence systems is likely between tooth and bone formation, we use bivariate regression to compare enamel carbonate and dentinal collagen $\delta^{13}C$ values taken from the lower portion of the tooth crown. This represents the latest forming part of the enamel, and values represent late childhood diet.

To assess adult dietary components, bone collagen isotopic values are plotted with reference to New Zealand foodweb values, sourced primarily from New Zealand colonial contexts (King et al. in prep).

3.5. $\delta^{13}C$ and $\delta^{18}O$ of tooth enamel bioapatite

Stable carbon and oxygen isotope analysis of dental enamel bioapatite was conducted at the Stable Isotope Laboratory, Max Planck Institute for Geoanthropology (formerly the Max Planck Institute for the Science of Human History, Jena, Germany). Dental enamel chips were taken from close to the CEJ of each sampled tooth for carbonate analysis. These chips were ground to a powder and pretreated by washing in 1% NaClO, followed by three rinses in MilliQ H_2O. 0.1 M acetic acid was then added for 10 min prior to rinsing again three times in MilliQ H_2O and freeze-drying (as per Lee-Thorp et al. 2012). Samples were weighed into borosilicate glass vials and sealed with rubber septa, then reacted with 100% phosphoric acid to evolve gas. Samples 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.

Carbonate $\delta^{13}C$ 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

Table 1
Details of the samples taken in this study. Note that tooth samples comprised both an enamel carbonate chip, and dentine for serial sampling if possible. Individuals without preserved dentine are indicated in the table, enamel samples were still taken from these individuals.

Cemetery	Individual	Likely population affinity	Sex	Tooth sampled (FDI system)	Bone collagen sample (Y/N)	Hair sample (length)
Lawrence, Ardrossan	A1	European	Male	16	Y, rib	N
Lawrence, Ardrossan	A8	European	Male	23	Y, rib	8 cm
Lawrence, Ardrossan	A12	European	Male	47. Enamel only, no dentine preserved	Y, femoral head	4 cm
Lawrence, Ardrossan	A17	European	Male	Unidentified molar fragment. Enamel only, no dentine preserved	Y, rib	N
Lawrence, Ardrossan	A18	European	Male	N	N	4 cm
Lawrence, Ardrossan	A21	European	Male	26	Y, ulna	N
Lawrence, Ardrossan	A22	European	Male	26	Y, thoracic vertebra	N
Lawrence, Ardrossan	A23	European	Male	17	Y, humerus	N
Lawrence, Ardrossan	A24	European	Female	43	Y, femur	16 cm
Lawrence, Gabriels	G1	Chinese	Male	27	Y, humerus	N
Lawrence, Gabriels	G2	Chinese	Male	27	Y, fibula	N
Lawrence, Gabriels	G3	Chinese	Male	17	Y, femur	16 cm
Lawrence, Gabriels	G4	Chinese	Male	23	Y, rib	12 cm
Lawrence, Gabriels	G7	Chinese	Male	27	Y, tibia	33 cm
Lawrence, Gabriels	G15	Chinese	Male	Unidentified molar fragment. Enamel only, no dentine preserved	Y, femur	4 cm
Lawrence, Gabriels	G25	Chinese	Male	36	Y, femur	N
Cromwell Cemetery	B1	European	Male	Unidentified M2	Y, rib	1 cm
Cromwell Cemetery	B2	Possibly Chinese	Male	42	Y, rib	N

precision was determined by analyzing repeat extracts from an in-house bovid tooth enamel standard that was prepared alongside the sample.

The results of oxygen isotope analysis have previously been published for all individuals (King et al. 2020) excepting those from the Cromwell cemetery. These results are therefore not focused on in this manuscript, but $\delta^{18}O$ values are used as a secondary proxy for region of origin for the two previously unpublished Cromwell individuals (see below).

3.6. Collagen/keratin $\delta^{13}C$ and $\delta^{15}N$ analysis

Serial sampling of dentine collagen followed 'Method 2' of Beaumont et al. (2013). Specifically, sampled teeth were half-sectioned longitudinally prior to analysis. Tooth half sections, and bulk bone samples weighing between 200 and 400 mg were mechanically cleaned of any particulates using a dental drill and diamond burr/cutting blade prior to demineralisation. Once cleaned the bulk bone samples, and half-sectioned teeth, were demineralised, gelatinised and lyophilised using a modified Longin method (Longin 1971, see King et al. 2020 for detail).

Hair samples were lifted in the field, taking care to label and retain original orientation relative to the scalp. Post-excavation, subsamples of approximately 10 strands of hair were removed from each oriented sample for analysis. Ten strands were sampled in order to ensure that at least some strands were in anagen (growth) phase (O'Connell et al. 2001). These analytical samples were cut into 1 cm increments prior to cleaning, as pilot work indicated that the cleaning process can fracture hair strands, resulting in loss of the orientation information. We acknowledge that samples are likely to contain a mixture of anagen/telogen phase strands and that this will impact the precision of the timings assigned to each increment (Williams et al. 2011). The growth phase of hair is assessable using characteristics of hair root morphology (Williams et al. 2011). However, in this study root morphology of the hair strands was not preserved, so we could not preferentially sample hair in anagen phase. Increments were cut using a sterilised surgical steel scalpel and placed into individual microcentrifuge tubes. 2 ml of 21 methanol: chloroform was added to each microcentrifuge tube. Tubes were then sonicated for 20 min. Solute was decanted and replaced. This process was repeated until the solution remained clear after sonication (as per O'Connell and Hedges 1999). Samples were then washed with deionised water, and allowed to air dry prior to weighing into tin capsules ready for analysis.

All collagen and keratin isotope analysis was undertaken at the Stable Isotope Biogeochemistry Laboratory (SIBL), Durham University using a Costech Elemental Analyzer connected to a Thermo Delta V Advantage isotope ratio mass spectrometer. Stable carbon and nitrogen isotopic compositions were calibrated relative to the VPDB and AIR scales using USGS 40, USGS 24, IAEA 600, IAEA N1 and IAEA N2. Measurement uncertainty was monitored using in-house collagen standards with well-characterized isotopic compositions. Using the equations suggested by Szpak et al. (2017) the standard error for the standards, samples and replicates analysed was ±0.2‰ for $\delta^{13}C$ and ±0.3‰ for $\delta^{15}N$.

Quality of results was established using standard parameters; C:N_{atomic} = 2.9–3.8 for hair (O'Connell and Hedges 1999), and 2.9–3.6 for bone/dentine, with weight percent carbon between 30 and 50, and nitrogen between 10 and 16 (DeNiro 1985; Guiry and Szpak 2020).

3.7. Strontium isotope analysis

Results of dietary isotope analysis are considered in light of a person's possible region of origin, established through both material culture and strontium isotope results. Strontium isotope results for the Lawrence sample have already been published in King et al. (2021a,b). Strontium isotope analysis of the two Cromwell individuals was undertaken as a part of this study. Strontium was purified from enamel samples following the method of Font et al. (2008), previously elaborated on in King et al. (2021a,b). Analysis was undertaken at the Northern Centre for Trace Element Analysis (Durham University) using a ThermoFisher Neptune Multi-Collector Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS), with purified samples diluted with 3% HNO_3 to run at a beam intensity of just under 20V. Strontium isotope ratios were normalized using repeated measurements of the NBS 987 standard ($^{87}Sr/^{86}Sr = 0.710240$). Procedural blanks were analysed alongside the sample to ensure lack of contamination.

4. Results

4.1. Mobility isotope analysis of the cromwell individuals

Sr isotope ratios and $\delta^{18}O$ values from the two Cromwell individuals are presented with reference to the previously published results from Lawrence on Fig. 3. B1 has a $^{87}Sr/^{86}Sr$ ratio of 0.70872 (± 0.000004), $\delta^{18}O = 26.9$‰ and plots close to individuals from the European cemeteries of Ardrossan St., and St. John's Milton. B2 has a $^{87}Sr/^{86}Sr$ ratio of 0.71029 (± 0.000014), $\delta^{18}O = 26.0$‰ and aligns more closely with individuals from the Chinese section of the Gabriels St. Cemetery in Lawrence.

4.2. Dietary isotope results

All dietary isotopic results from this study, including collagen quality indicators are given in full in Supplementary Table 1, and presented visually in supplementary Figures 1 and 2. In the following sections, however, we describe the main patterns observed in the data.

4.3. Dentine isotope results – weaning patterns

It is notable that many individuals do not show clear signs of weaning in their dentinal isotopic values, potentially having been fully weaned prior to the first datapoint in the sampled tooth (Fig. 4a gives an example of this pattern). Fig. 4b, on the other hand, highlights the typical weaning curves seen in the sample, including the 'long' weaning curve seen in many of the Chinese individuals. Table 2 outlines the isotopic changes observed in each individual's dentine isotopic records and how they might relate to weaning behaviour.

4.4. Childhood diet based on dentinal collagen and apatite values

To better characterise post-weaning diet, results of dental enamel bioapatite $\delta^{13}C$ and dentine collagen $\delta^{13}C$ (Supplementary Table 2) are reported in Fig. 5 with reference to the bivariate regression lines established by Froehle et al. (2010). This compares bioapatite and dentine collagen values taken from the lower portion of the crown. The lower portion of the crown is the latest forming part of the enamel, and it is hoped that values represent broadly similar periods of time. G7 and G25 are excluded from this analysis as they do not appear to have been weaned beyond the end of crown formation and we aim to look at post-weaning diet.

This analysis shows that all individuals have childhood diets dominated by C_3 resources. It is, however, notable, that all Chinese individuals from the Gabriels St Cemetery have values above the pure C_3 line, indicating some marine/C_4 protein input into diet, while European Ardrossan St. individuals seem to have had an almost pure C_3 protein input.

4.5. Dentine and bone collagen differences

Almost all individuals have marked differences between their end of childhood (tooth root) and adulthood (bone) isotopic values – only two individuals (G7 and G25) have values which remain essentially unchanged. The majority of individuals have increased $\delta^{13}C$ and $\delta^{15}N$ values (Table 3) in adulthood relative to their childhood. This is not, however, a universal trend.

4.6. Adult diet

Fig. 6 plots bone collagen values relative to foodweb $\delta^{13}C$ and $\delta^{15}N$ values from colonial Central Otago. All individuals fall broadly within the same isotopic space, with terrestrial herbivores and C_3 plants likely making up the bulk of their diet. However, there is a general trend toward higher $\delta^{15}N$ in the Chinese individuals.

4.7. End of life isotopic changes (hair analysis)

Hair isotopic results are presented in full in Supplementary Figures 1 and 2. Most individuals have hair isotopic values which align well with their bone collagen isotope values, and vary by less than 1‰ across the hairs' length, indicating a lack of major dietary change through this portion of adult life. However some individuals do have more significant changes visible within their hair isotopic values. A8 (Fig. 7A), for example, has unusually regular N isotopic fluctuations of approximately

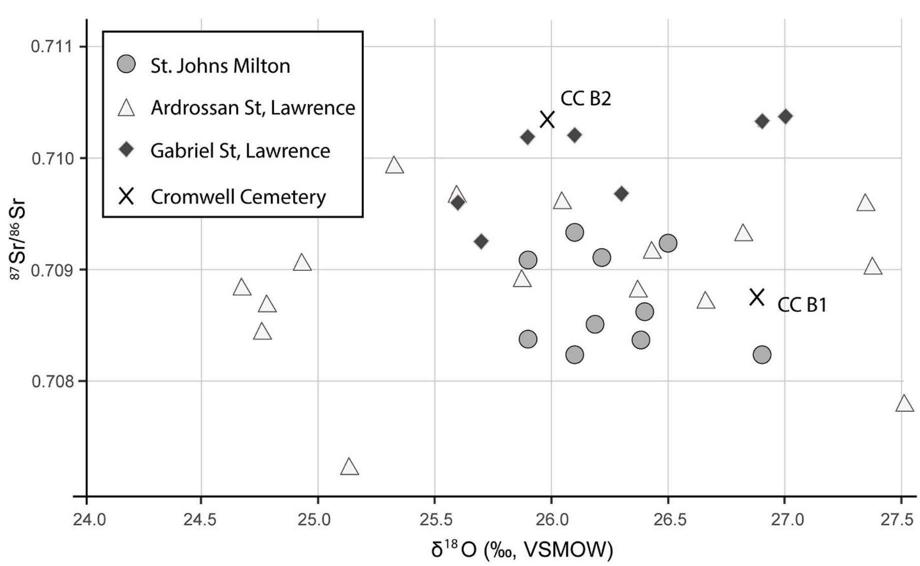

Fig. 3. Cromwell individuals' mobility isotope results relative to previously published sites (King et al., 2020, 2021). Note that some isotopic outliers from previously published work are not shown on this figure in order to increase visibility of the Cromwell individuals.

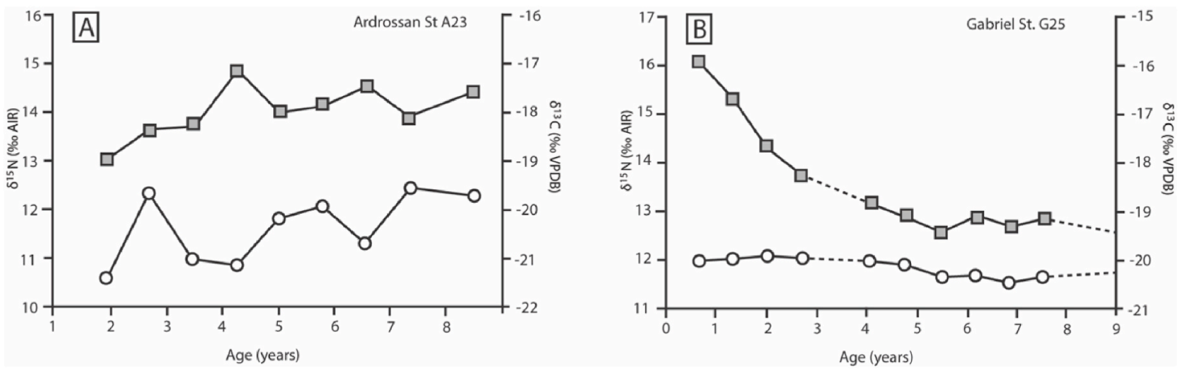

Fig. 4. Examples of dentinal isotopic patterns from this study. (A) shows a profile with no visible weaning (A23), likely because weaning was complete prior to the first datapoint. (B) shows a typical weaning curve from individual G25, with weaning complete around 5.5 years of age.

Table 2
Isotopic changes and their possible relationship with weaning in the study sample. Possible start of weaning assessed visually based on when isotopic values begin to decrease. Age of cessation of weaning estimated using point at which both $\delta^{15}N$ values and $\delta^{13}C$ begin to flatten.

Individual	Start of $\delta^{15}N$ and $\delta^{13}C$ value decrease (possible start of weaning)	End of $\delta^{15}N$ and $\delta^{13}C$ value decrease (possible end of weaning)	Notes
CC B1	Prior to 2.8 years	Difficult to interpret due to late start of profile	No datapoints prior to 2.8 years, so this individual could have been fully weaned before this time.
CC B2	Prior to 1.2 years	3 years	Possible that full weaning occurred before 1.2 years of age and that changes beyond this are childhood dietary change.
A1	Prior to 1.3 years	3.5 years (end of C decrease)	N continues to change beyond this point, but without corresponding changes to C
A8	Prior to 2.8 years	Difficult to interpret due to late start of profile	Possible that full weaning occurred before 2.8 years of age
A21	Prior to 0.6 years	1.8 years	C difficult to interpret as no clear curve here.
A23	Prior to 3 years	Prior to 3 years	No weaning curve visible
A24	Prior to 1.2 years	Prior to 1.2 years	No weaning curve visible
G3	Prior to 3 years	5.2 years	Possible that full weaning occurred before 3 years of age and that changes beyond this are childhood dietary change.
G4	Prior to 0.9 years	2.5 years	N continues to change beyond this point, but without corresponding changes to C
G7	Prior to 2.8 years	4.7 years	Possible that full weaning occurred before 2.8 years of age and that changes beyond this are childhood dietary change.
G25	Prior to 0.6 years	5.5 years	Very clear weaning curve, although surprisingly late cessation of weaning.

1‰ over a 6 month period, with similar but less obvious changes in $\delta^{13}C$ values.

A24's hair isotopic record (Fig. 7B) represents almost 1.5 years of life. It displays some of the most variable isotopic values in the sample. $\delta^{13}C$ values broadly co-vary with $\delta^{15}N$ values across the length of the hair. At 16 months prior to death A24's isotopic values begin to decrease, with $\delta^{15}N$ lowering by 1‰ over the course of 8 months. $\delta^{15}N$ values then increase over the next 4 months, rising sharply by 1.5‰ at 6 months prior to death. Following this, $\delta^{15}N$ values decrease sharply by over 2‰ across 3 months, with corresponding but smaller magnitude changes to $\delta^{13}C$. Isotopic values then rise again close to death.

Finally, G7 (Fig. 7C) has the longest hair of all those in the sample (32 cm), giving us insight into over 2.5 years prior to their death. This time depth brings to light significant changes to isotopic values between 7 and 10 months before death. At this point $\delta^{15}N$ values decrease, ending up approximately 1‰ lower than at the tip of the hair strand. More significant is the sharp decrease in $\delta^{13}C$ values during this period (a 3‰ change). These patterns, and interpretations of isotopic change are explored more fully below.

5. Discussion

Collating all isotopic results for these individuals allows us to create what essentially amount to 'isotopic biographies' for each person, reconstructions of diet and potential metabolic change through the life course. This is, in our opinion, one of the most powerful aspects of serial sampling for isotopic analysis. Extended isotopic biographies for each individual are given in full in the Supplementary data associated with this manuscript (Supp File 1). Within the discussion here, however, we bring together the data and describe trends relating to various parts of life history.

5.1. Analysing weaning patterns

As with most studies interested in isotopically identifying weaning behaviours, we did not find any clear patterns in weaning behaviour (Beaumont et al. 2015; Craig-Atkins et al. 2018; King et al. 2018; Kendall et al. 2021). Interpretation of weaning behaviour in the past is very difficult, as a myriad of cultural, environmental and individual factors play into maternal decision-making processes surrounding how and when weaning is implemented (Tomori et al. 2018; Gowland and Halcrow 2020; Kendall et al. 2021). People on the goldfields likely came from a variety of European and Chinese cultural contexts, where different cultural expectations, as well as other economic and environmental factors, led to idiosyncratic breastfeeding and weaning behaviours.

However, it is notable that many individuals in the sample experienced what might be called 'late' weaning, with childhood isotopic values not becoming stable until around three or more years of age. This is particularly true of many of the Chinese individuals in the sample, some of whom seem to not have been fully weaned until four or five years of age (e.g. G3, G7, G25). Late weaning is also apparent in A1, an individual of likely European ancestry. This pattern is therefore not restricted to those of Chinese origin.

There is some ethnographic evidence that late cessation of weaning

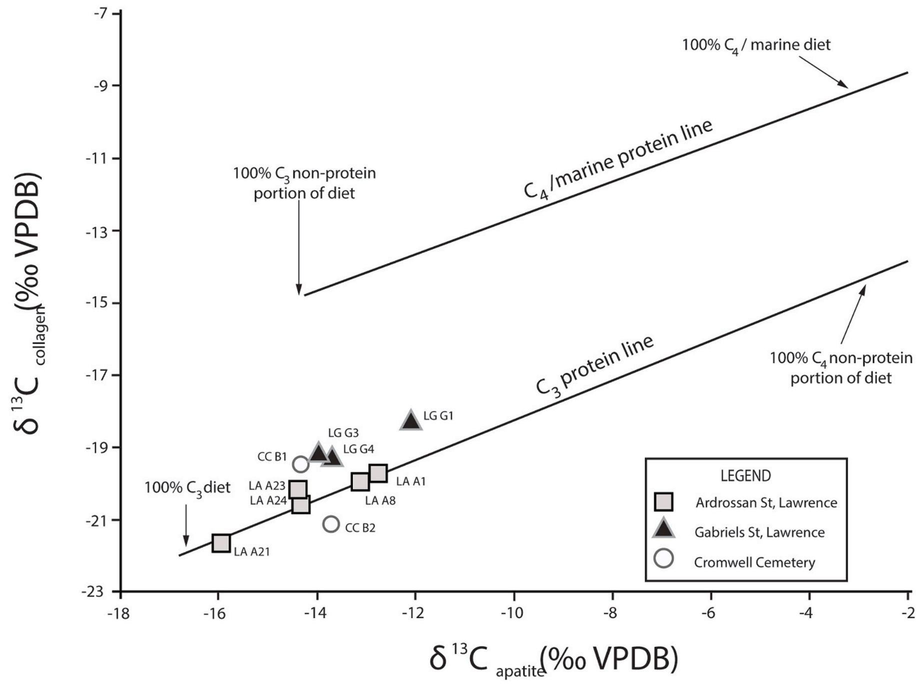

Fig. 5. Lower crown $\delta^{13}C_{apatite}$ values plotted against dentine increment $\delta^{13}C_{collagen}$ values corresponding to approximately the same age of formation. Regression lines shown are those proposed by Froehle et al. (2010) indicating likely dietary inputs. LA = Ardrossan St cemetery, LG = Gabriels Street and CC = Cromwell cemetery. Burial numbers are preceded by an A at Ardrossan St, G at Gabriels Street and B at Cromwell.

Table 3
Differences between childhood (tooth root) and adulthood (bone) isotopic values in individuals analysed. Individuals in italics have negligible difference in values - only just outside analytical error.

Individual	Tooth root $\delta^{13}C$ (‰)	Bone $\delta^{13}C$ (‰)	Difference	Tooth root $\delta^{15}N$ (‰)	bone $\delta^{15}N$ (‰)	difference
CC B1	−19.5	−18.8	+0.63	14.7	13.1	−1.6
CC B2	−20.0	−18.6	+1.4	12.3	13.3	+1.0
G3	−19.4	−19.7	−0.3	12.4	13.0	+0.7
G4	−19.4	−18.6	+0.9	12.1	13.5	+1.4
G7	*−19.2*	*−18.8*	*+ 0.4*	*13.5*	*13.1*	*−0.4*
G25	*−20.4*	*−20.3*	*+ 0.1*	*13.0*	*12.7*	*−0.3*
A8	−20.6	−17.8	+2.8	11.5	12.2	+0.7
A21	−20.8	−20.5	+0.3	11.4	12.1	+0.7
A24	−20.5	−17.7	+2.8	14.0	12.9	−1.0

was considered the ideal in Qing dynasty China (Furth 1987), increasing both the health of the infant and the likelihood of long inter-birth intervals (Wolf and Engelen 2007). Although the ideal is generally reported as three years of age (Furth, 1987), some early 1900s accounts record continued breastfeeding until four or five years of age during the late 1800s, typically among the rural poor (Platt and Gin 1938). This use of the contraceptive effect of breastfeeding to maximise the interbirth interval, and avoid having another weaned infant to compete for already scarce food resources, has also been reported in rural English mothers from this time period (Crawford 2010), and may be a factor behind A1's late weaning.

The accepted age for weaning in Europe in general, and the UK in particular, however, was earlier than in China. Sources generally held that it should be initiated by 6 months and complete by 18 months of age (Wickes 1953). This age range is prior to the first isotopic datapoint for many of the individuals analysed, thus it is hard to evaluate how well this recommended pattern was held to. However, one individual (A24) shows no sign of breastfeeding, and was likely fully weaned prior to 1.2 years of age. This aligns well with observations in other studies (Nitsch et al. 2011; Britton et al. 2018). These studies in the UK have suggested that this kind of 'early' weaning was typical of both urban mothers who were compelled to return to work (and wages) as soon as possible after

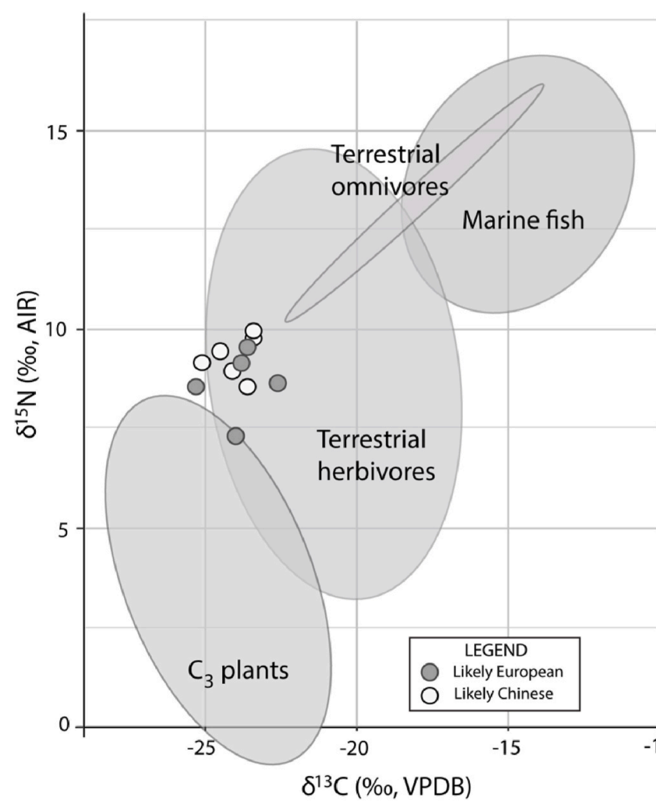

Fig. 6. Bulk bone collagen results plotted relative to foodweb values (King et al. in prep). Note that all human values have been corrected for the diet-collagen offset (−3.5‰ for $\delta^{15}N$, and −4.8‰ for $\delta^{13}C$, as per (Fernandes et al., 2014).

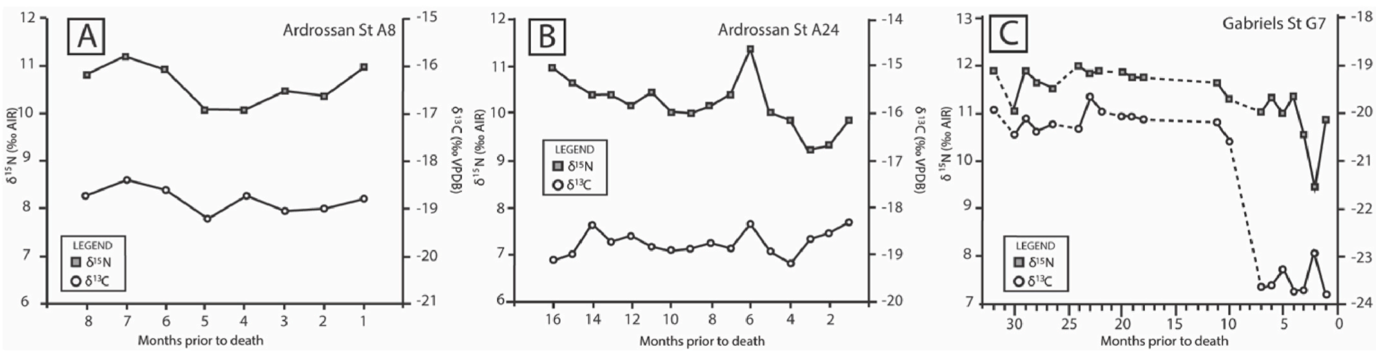

Fig. 7. Examples of isotopic patterns seen in hair profiles. (A) A8, showing possible seasonal variation in resource use. (B) A24, showing isotopic spikes and (C) G7, showing a significant dietary shift.

birth (Wickes 1953; Fildes 1995), and the wealthy who chose to dry-feed rather than face the inconvenience of breastfeeding (Fildes 1986).

5.2. Adult diet – population differences and evidence for seasonal resource use

Both bone collagen and hair isotopic results show that diet for all but one individual was dominated by terrestrial C_3 crops and protein resources, similar to results from the contemporary rural settlement of Milton (King et al. 2021). Although bone collagen results were broadly similar between the two Lawrence cemeteries these measurements represent a homogenised signal from a period of life when the individuals were probably highly mobile. It is difficult to tell how much of their bone collagen isotopic signal is from their ‘home’ diet, and how much reflects life at the diggings. The better time resolution afforded by hair analysis gives more insight into this and suggests that there were some dietary differences on the goldfields between those buried in the European Ardrossan St. cemetery and those in the Chinese section of Gabriel St. Probable Chinese individuals are set apart by their lower $\delta^{13}C$ values, likely reflecting the importance of rice in their diet (Piper 1988). These hair values contrast with the collagen/apatite values (Fig. 5) of the Chinese individuals. These results indicate more C_4 or marine resource input into the diet earlier in life and imply that for most of the Chinese individuals experienced a change in diet between childhood/early adulthood and later life in New Zealand.

Overall, these analyses suggest that hair isotopic values may be used to differentiate individuals of Chinese origin from Europeans in mixed colonial cemetery contexts. However, caution is needed as the pattern may not be applicable to other goldfields which will have had differences in resource availability.

The isotopic results indicate that there was variation in meat consumption patterns in both cemetery populations. G15 and A8 have much lower $\delta^{15}N$ values than others in their cohorts, perhaps reflecting their inability to source or to afford as much meat. Although contemporary sources describe how early arrivals to the diggings were often without meat for weeks or months, as runholders (sheep farmers) could not keep up with demand when the rush first started (Campbell 1982), this period of low meat supply was short-lived. Supply chains were quickly set up to service the diggings, and unless A8 was one of the earliest arrivals to the area it is unlikely that this would have affected him. G15, as a later Chinese migrant almost certainly had access to meat resources, if he could afford them.

Only A8 seems to have evidence for a pattern of fluctuating food availability in his hair isotopic profile, while others maintain a more consistent diet. If A8 was one of the earlier arrivals to the diggings he would have been more reliant on seasonally available resources than those on the goldfields once supply chains had been established. Alternatively, as mentioned above, fluctuations in diet may represent changing fortunes on the goldfields, with A8 only being able to afford meat at certain times. Those with a more consistent diet likely had access to the stores, and enough money to buy resources that would buffer against seasonal insufficiencies. Alternatively, initial paleopathological analysis indicates that A8 suffered multiple facial trauma prior to death which may have impacted his ability to chew tough foods like meat, resulting in short-term changes to his diet (Snoddy et al. 2023).

Aside from G15, the other individuals buried in Gabriel St have higher $\delta^{15}N$ values than those in Ardrossan St. This is true of both hair averages and bone collagen isotope values and suggests that the Chinese may have had better access to meat both prior to their arrival in Otago, and on the Otago goldfields than the Europeans did. The Chinese on the goldfields were marginalised by the Europeans and we expected this to result in limited access to high trophic level resources, however this does not appear to have been the case. Instead, it is possible that the Chinese emphasis on community afforded them better collective access to meat. Chinese miners were much more community-oriented than their European counterparts. Their camps were centred on Chinese stores and lodging houses, they took care of those who were out-of-work and fed newcomers to the diggings (Ng 2003). In addition to this the Chinese sojourners had established importation networks to the British colonies which included salted and dried fish supplies (Bowen 2012), and access to canned fish (Piper 1988). The higher $\delta^{15}N$ values of the Chinese may reflect their higher marine resource use relative to European miners, perhaps related to their desire to retain the fish-based food traditions of their homeland (Piper 1988).

5.3. The value of hair isotopes for looking at life close to death

Life on the goldfields has been heavily mythologised, and the realities of people’s individual experiences lost within these narratives. Those sampled in this study lay in unmarked graves, their identities are unknown, and their stories have been lost. The preservation of their hair, however, gives us a chance to reconstruct their last months of life and better understand them as people. Studying diet via isotopes in hair has revealed significant variation in food choices and/or availability even among the few individuals in our sample. This shows that while the goldminers may have shared some experiences of hardship, there is no single story that defines the ‘goldfields life’.

Looking at hair with this level of time resolution is particularly useful for those individuals with the longest hair in the sample (G7 and A24). These profiles allow us to identify potentially important life events and their implications. For example, dramatic changes in isotopic values approximately 10 months prior to the death of G7 may be linked to any number of processes that may have caused a significant change in diet (see Supp File 1). Their isotopic values never return to their earlier signature, indicating that this change was permanent. With decreases in both $\delta^{13}C$ and $\delta^{15}N$ values it is most likely that this dietary change involved decreased consumption of marine fish, or C_3 foddered terrestrial meat sources close to time of death.

It is possible that this dietary change is associated with movement between areas of differing ecology or resource availability. Chinese movement in terms of visiting China and/or between the goldfields of New Zealand was well-documented by Alexander Don (cited in Ng, 1993; Vol 4). It is possible that G7's changing dietary isotopes reflect one of these movements between places (e.g. from a more coastal goldfield (such as Round Hill) to the inland ones of Lawrence). Alternatively, this dietary change may simply reflect a sudden lack of availability of certain resources on the goldfields and/or a change to different animal consumption patterns or rearing practices. For example, a disruption in supply of fish to the goldfields, or a shift to grass-fed rather than maize fed meat sources could cause this kind of shift in values.

Analysis of another individual's hair profile has given insight into potential stress episodes. A24's long and variable isotopic record is difficult to interpret (see Supp File 1) but their changeable $\delta^{15}N$ values, including some dramatic spikes, across a 16-month period may be suggestive of sporadic meat insufficiencies, short-lived periods of high marine food consumption, acute periods of nutritional stress, or even stresses associated with pregnancy and lactation. Other analyses undertaken on this individual shows that they had toxic levels of mercury in their hair, that were orders of magnitude higher than all others from the same cemetery samples. We have interpreted this as likely medicinal use of mercury in response to illness (Parker et al. 2023) during hair growth. Regardless of the cause, their isotopic variability suggests that their life close to death was tumultuous, involving frequent changes to diet and/or health status.

6. Conclusion

Individual-focused bioarchaeological research is one of the only ways to bring to light the lives of 'ordinary' colonial individuals whose presence in historical records is generally minimal. In this study, we highlight how using isotopic evidence from tissues forming at different life stages, some of which can be sequentially sampled, can allow extremely detailed reconstruction of dietary change and interpretation of life events. We use clear changes to dietary regime to identify weaning behaviour and possible timing of relocation to New Zealand. We show that the only female in the sample is also the individual with the most isotopic variability, including spikes in isotopic values which likely correlate to periods of physiological or nutritional stress. This research also provides initial evidence that Chinese miners on the goldfields retained an isotopically distinct diet to the Europeans working in the same area. This not only highlights the retention of cultural differences during the colonial period but may also have useful implications for the identification of Chinese individuals in historic New Zealand sites.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2023.105836.

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