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ORIGINAL PAPER

Isotopic insights into diet and health at the site of Namu, Taumako Island, Southeast Solomon Islands

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Abstract A relatively new development to the milieu of archaeological techniques routinely used in the Pacific Island region, the stable isotope analysis of human skeletal and dental remains has provided important insights into diet, methods of subsistence and also intra-population variation in diet that may be related to age, sex or status. This study is a stable isotope analysis of one of the largest skeletal samples discovered in the Pacific Islands, from the Namu burial ground (ca. 700–300 BP) located on the small island of Taumako, Southeast Solomon Islands. Here, the stable isotope ratios of carbon and nitrogen of bone collagen (n = 142, $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$) and tooth dentine (n = 86, $\delta^{13}C_{tooth}$ and $\delta^{15}N_{tooth}$) are analysed to assess adult (survivor) and subadult (non-survivor) diets and patterns of breastfeeding, which also provided insight into possible maternal and foetal/perinatal stress in the population. The $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ results suggested that the adolescents and juveniles who died were eating foods from lower trophic levels than those who survived to adulthood, especially the males. The $\delta^{13}C_{tooth}$ and $\delta^{15}N_{tooth}$ stable isotope values suggested that, during the ages of 5–9 years, individuals were eating more terrestrial and less marine foods than later in life as adults. The sex differences in adult diet ($\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values) were not present as children ($\delta^{13}C_{tooth}$ and $\delta^{15}N_{tooth}$ values). The intra-population variation is discussed in the context of wider Pacific island diet and cultural processes and recent developments in understanding stress and disease processes on human stable isotope values.

Keywords Pacific islands · Stable isotope analysis · Palaeodiet · Subadult diet · Carbon · Nitrogen

Introduction

The Pacific Islands encompasses thousands of islands from New Guinea in the west to Micronesia in the north and Rapa Nui (Easter Island) in the east. The settlement history of the region is complex; the earliest evidence of human occupation can be found in New Guinea dating to 40,000 BP, and possibly earlier (Summerhayes et al. 2010). People associated with the Lapita culture arrived in the Bismarck Archipelago ca. 3400 BP and over the next 1000 years spread north, east and south, eventually settling the previously uninhabited islands of New Caledonia, Vanuatu, Fiji, Tonga and Samoa (Kirch 1997; Spriggs 1997; Summerhayes 2001). Subsequent expansion and settlement occurred in Polynesia and Micronesia, and the presence of a pre-Columbian Polynesian chicken bone (*Gallus gallus*) in Chile suggests that Polynesians reached South America ca. 1300–1400 AD (Storey et al. 2007). Over the past 20 years, bioarchaeology in the region has blossomed, providing insights to the health and past lifeways of Pacific Islanders (Bedford et al. 2011; Buckley et al. 2014; Buckley and Oxenham 2016; Buckley 2007; Buckley and Tayles 2003b; Buckley et al. 2010; Buckley et al. 2008; Douglas et al. 1997; Kinaston et al. 2016a, b; Littleton and Kinaston 2008; Pietrusewsky 2005; Pietrusewsky 2006; Pietrusewsky et al. 1997; Stantis et al. 2016b; Stodder et al. 2016). A growing number of stable isotope studies have successfully been used to understand specific

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cultural and economic aspects of these past societies, which has not been possible using other research methods, such as macroscopic analysis of human remains and archaeozoological assessments of subsistence (see review by Kinaston and Buckley 2013).

The first Pacific Island stable isotope studies for palaeodietary reconstruction were conducted on a number of human and faunal remains, along with modern fauna and flora, from a wide variety of sites (Davidson and Leach 2001; Leach et al. 1996; Leach et al. 2003), including one of the only Lapita burial grounds discovered at the time located on Watom Island, Papua New Guinea (Leach et al. 2000). The number of studies increased from the mid-AD 2000s as researchers began realizing the potential of stable isotope analysis to provide direct evidence for diet in the past (Kinaston and Buckley 2013). In addition to discerning the palaeodiet at each site, these studies focussed on a range of more specific topics relevant to the region including adaptation to island environments (Ambrose et al. 1997; Commendador et al. 2013; Kinaston et al. 2016a, b; Kinaston et al. 2014b; Kinaston et al. 2013c), temporal changes in diet (Allen and Craig 2009; Commendador et al. 2013; Field et al. 2009; Jones and Quinn 2009; Kinaston et al. 2014a; Pate et al. 2001; Richards et al. 2009; Valentin et al. 2014; Valentin et al. 2011) and age-, sex- and status-related variation in diet (Kinaston et al. 2013a; Kinaston et al. 2013b; Kinaston et al. 2009; Kinaston et al. 2014b; Stantis et al. 2015; Valentin et al. 2006).

As a result of poor post-mortem bone preservation in tropical environments, small excavation sizes, difficulty finding sites (especially in coastal areas) and cultural reasons for not excavating or for the immediate reburial after exhumation (mostly in Polynesia) (Turner-Walker 2008; Waldron 1994), the sample sizes for bioarchaeological investigations in the Pacific Islands, including stable isotope analyses, can be limited and may contain non-burial remains. As with most scientific research, a large sample size allows for intra-population comparisons using statistical analyses, which may provide a more nuanced understanding of certain aspects of a past community, such variation in diet that may be related to age, sex and status (Waldron 1994). Importantly, larger skeletal samples are also more likely to contain subadult individuals, the inclusion of whom results in a more accurate representation of the demography of the living population that the sample was derived from (Lewis 2007).

There is a paucity of stable isotope research focussed on subadult remains from the Pacific islands because of the abovementioned small size of the skeletal assemblages discovered in the region and, in some cases, the interment of subadult remains in areas other than the 'adult' burial ground (e.g. the Teouma site, Bedford et al. 2011; Bedford et al. 2010; Buckley et al. 2008). However, research focussed on subadult individuals can provide important information about past communities, as children are considered barometers of population health in bioarchaeological studies (Lewis 2007). The diets of infants and children would have had a direct impact on their health and ultimate survival (Lewis 2007). Therefore, understanding their diet through stable isotope analysis can provide insights into survivorship, adaptation and cultural processes in the past. A few notable studies have been conducted on Pacific island subadults including Kinaston et al. (2009), which focussed on foetal and perinatal stress in a Lapita population from Teouma, Vanuatu; Kinaston et al. (2013b) which included three subadults from a late prehistoric population from Papua New Guinea; Kinaston et al. (2014a) which analysed five subadults from a Lapita-age site on Uripiv island, Vanuatu, and Stantis et al. (2016a) which assessed 1 subadult and 16 adult and subadult teeth to assess childhood diet.

The current study is a stable isotope analysis of adult and subadult diet from one of the largest Pacific Island skeletal samples discovered to date ($n = 226$), the Namu burial ground on the island of Taumako in the Southeast Solomon Islands (Fig. 1). Carbon and nitrogen stable isotope ratios of bone collagen are used to address questions regarding age-related differences in diet at the site and the possible duration of breastfeeding. Additionally, carbon and nitrogen stable isotope ratios of tooth collagen of adults (the survivors of childhood) and of the bone and tooth collagen of infants and children (the non-survivors) are used to investigate possible dietary differences between these two groups and also assess if there were sex-related differences in diet during childhood. The carbon and nitrogen stable isotope values of adult female and foetal/infant co-interments are also assessed to further investigate the validity of using young subadults in palaeodietary studies.

Materials and methods

The site and skeletal sample

Taumako is a small (three miles long and one mile wide) volcanic island located in the Duff Island group in the far east of the Solomon Islands (Fig. 1) (Sheppard and Pavlish 1992). The Duff Islands themselves are part of a larger group of islands, the Santa Cruz Group (Leach and Davidson 2008). Taumako is home to one of 18 societies in the Western Pacific Islands known as Polynesian Outliers. These communities speak a Polynesian language and are thought to represent east-west 'blowback' movements from Polynesia into the Western Pacific (Kirch 1984). Archaeological evidence from Taumako supports that the island was first settled ca. 2700 BP by people associated with the Lapita Cultural Complex. Polynesian speakers arrived on Taumako possibly around the mid-second millennium AD, but throughout the prehistoric sequence, there was considerable contact with other islands in the region (Kirch 1984; Leach and Davidson 2008).

The Namu burial site was excavated by Foss Leach and Janet Davidson in 1977 (Fig. 2). An initial aim of the excavation of the Namu burial ground was to analyse the remains of the people

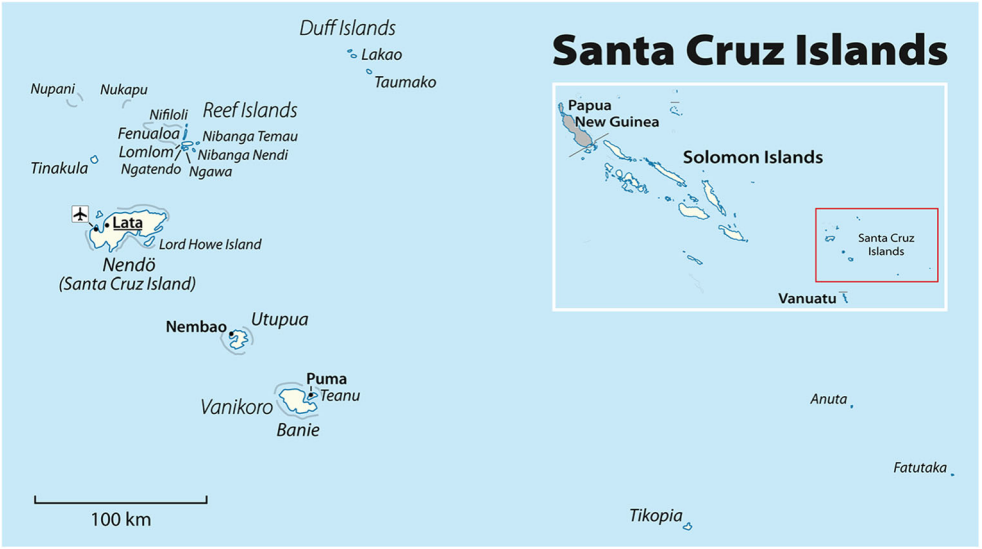

Fig. 1 The location of Taumako Island, Duff Islands Group, Southeast Solomon Islands (by Maximilian Dörrbecker https://commons.wikimedia.org/w/index.php?curid=14481571)

inhabiting a Polynesian Outlier in order to understand population affinities (Leach and Davidson 2008). The Namu site is composed of a low mound, 200 m inland from the ocean, 70 cm above the surrounding ground and 7–8 m in diameter.

Calibrated radiocarbon dates from six human bone samples suggest that the burial ground was in use from around 1220 to 1745 AD at the maximum range, with a more conservative range of 1275 to 1655 AD (Leach and Davidson 2008). The burial ground was intensively used during this time, and it has been suggested from the close proximity of the burials to one another that individuals were interred in family groups (Leach and Davidson 2008). In a number of instances (n = 7), either one or two subadult individuals were interred in the same grave as an adult female, possibly indicating a double or multiple burial of a mother with her child or relatives (J. Davidson personal comment). There were very few faunal remains discovered at the site, and these were unable to be analysed for the current analysis. The limited remains included three rat bones (likely *Rattus praetor*), fragments of marine turtle carapace, seven elasmobranch vertebrae and single or very few elements from the Coridae/Labridae fish family, *Monotaxis grandoculis* and unidentified teleost fish. Leach and Davidson (2008) suggested that these small bones might have been introduced to the site as charms rather than food debris. Material culture was found associated with some burials including shell money (*kolokolo*), large shell *Tridacna* discs (*tavi*), *Conus* discs, *Nautilus* discs, *Nautilus* rhomboid-shaped units, ivory reels and bobbles (associated with the coveted red-feather money used for bride price), *Cassis* knee ornaments, special amulets, worked flying fox teeth and shell nose ornaments (Davidson and Leach 1991; Leach and Davidson 2008). A previous isotopic study studied the diet of 99 adult individuals from the Namu burial ground and found dietary differences between males and females and high-status and low-status individuals, as inferred from burial wealth (Kinaston et al. 2013a).

Fig. 2 Photo of the excavation of the Namu burial ground on Taumako (photo courtesy of Janet Davidson and Foss Leach)

An early report by Houghton identified 201 individuals in the Namu skeletal sample (published in Leach and Davidson 2008). A reanalysis by Buckley (2001), using standards from Buikstra and Ubelaker (1994), found 226 individuals, 133 of these representing adults (aged 17+ years), and these age and sex estimates are used in the current study of 149 individuals (See Online Resource 1). In this study, the ages of the subadult individuals were estimated using dental and skeletal development (Buikstra and Ubelaker 1994; Moorrees et al. 1963a; Moorrees et al. 1963b; Ubelaker 1989) and subsequently categorized into five age cohorts: foetal/perinatal (died before or around the time of birth), infant (0.1–1.0 year old), young child (1.1–5.0 years old), juvenile (5.1–9.0 years) and adolescent (9.1–16.9 years) (n.b. no children aged 3.1–5.0 years were found). The age categories were defined in such a way to be able to investigate infant and childhood diet, in addition to grouping the subadults whose biological ages matched those of the formation time of the first molar distal root tissue (formed between the ages of 5 and 9 years) that was sampled to understand the childhood diet of the adults and adolescents.

Evidence of widespread treponemal disease, yaws (*Treponema pertenue*), was observed on the cranial and postcranial skeletons of a number of individuals buried in the Namu cemetery (Buckley and Dias 2002; Buckley and Tayles 2003a). Yaws is a chronic infectious disease that typically affects children. Without antibiotic treatment, yaws can persist throughout a person's life, beginning with skin lesions and culminating with diffuse osteoblastic bone production of (typically) the lower limbs, especially the tibia, in addition to the forearms, humeri, clavicle and crania. The tertiary phase of yaws affects adults and is characterized by destructive lytic lesions specific to treponemal disease known as gumma (Buckley and Tayles 2003b). As will be further discussed, the high prevalence of treponemal disease, and other pathogens such as malaria, affecting the Taumako skeletal sample may cause variation in the stable isotope values analysed from bone collagen, and therefore, the possible influence of yaws on bone collagen stable isotope values is also tested in this study.

Stable isotope analysis

Carbon stable isotope ratios ($\delta^{13}C$) are used to determine if certain types of plants with differing photosynthetic pathways were eaten (C_3, C_4 and CAM) and to assess marine vs. terrestrial food consumption patterns (Katzenberg 2008). This is because C_4 plants and marine systems typically display higher $\delta^{13}C$ values compared with C_3 plants and terrestrial systems respectively. The $\delta^{13}C$ values of CAM plants generally fall in between those of C_3 and C_4 plants (DeNiro and Epstein 1978; Schwarcz 1991). Dietary differences can be observed in bone collagen and bioapatite of humans and animals as carbon from the diet is used to synthesize bone and tooth tissue. The carbon stable isotope ratios of bone collagen in cortical bone are generally representative of dietary protein because this carbon is routed mainly from dietary amino acids (Froehle et al. 2010; Jim et al. 2004; Kellner and Schoeninger 2007). The $\delta^{13}C$ values of bone apatite reflect the whole diet because carbon from all macronutrients (protein, lipids and carbohydrates) is utilized for its synthesis (Ambrose 1993; Ambrose and Norr 1993).

Bone collagen $\delta^{13}C$ values are approximately 5‰ higher than the diet (diet-tissue spacing) if all dietary components are monoisotopic (e.g. all from a C3 terrestrial ecosystem), although the exact dietary offset ($\delta^{13}C_{diet\text{-}collagen}$) appears to be influenced by the isotopic composition of the dietary macronutrients (Ambrose and Norr 1993; Froehle et al. 2010; Tieszen and Fagre 1993). Trophic level enrichment of $\delta^{13}C$ values has been found to be small, about 0–2‰, between consumer and prey collagen values (Bocherens and Drucker 2003).

Nitrogen stable isotope ratios ($\delta^{15}N$) in bone collagen are only representative of the protein portion of the diet because other macronutrients (lipids and carbohydrates) do not contain nitrogen (Ambrose 1993). There is a stepwise enrichment in $\delta^{15}N$ values of 2–4‰ with each trophic step (Hedges and Reynard 2007). As a result, the $\delta^{15}N$ values of bone collagen are a reflection of the trophic position of an organism. The analysis of $\delta^{15}N$ values can help differentiate between the consumption of plants (lower values) and animals from higher trophic levels than plants (higher values). Both marine and freshwater aquatic systems display longer food chains and consequentially more trophic enrichment compared with terrestrial systems (DeNiro and Epstein 1981; Minagawa and Wada 1984). As a result of the trophic effect, breastfeeding results in the enrichment of infant tissues with ^{15}N (Fogel et al. 1989; Fuller et al. 2006a; Katzenberg et al. 1996; Tsutaya and Yoneda 2015). The increase in $\delta^{15}N$ values of infant tissues (including bone collagen, tooth dentine and fingernails) and the subsequent decrease in these values when subadults are fed supplementary foods have been observed in numerous studies from around the world (Fuller et al. 2006a; Fuller et al. 2006b; Jay 2009; Jay et al. 2008; Nitsch et al. 2011; Prowse et al. 2008; Tsutaya and Yoneda 2015).

Used in conjunction with $\delta^{13}C$ values, the analysis of $\delta^{15}N$ values can help discern between the consumption of marine (or freshwater) and terrestrial foods in the diet. Certain types of plants, such as legumes, and specific environments like mangroves and coral reefs have a prevalence of N_2-fixing bacteria which act to lower the $\delta^{15}N$ values, which will be reflected in the tissues of higher consumers (Bashan and Holguin 2002; Keegan and DeNiro 1988; Schoeninger and DeNiro 1984; Yamamuro et al. 1995). Certain environmental factors, such as aridity (Heaton et al. 1986; Pate and Anson 2008; Schwarcz et al. 1999), and farming practices, especially the use of manure on crops (Bogaard et al. 2007; Fraser et al. 2011), may alter the $\delta^{15}N$ values of plants that form the base of the food web and should be considered if domesticated or wild faunal $\delta^{15}N$ values appear anomalous for a site where these situations may potentially occur.

The $\delta^{13}C$ and $\delta^{15}N$ values of bone collagen from cortical bone are representative of approximately the last 10 years of the protein diet of an adult human (Hedges et al. 2007). As a result of elevated rates of bone modelling and remodelling in growing individuals, the $\delta^{13}C$ and $\delta^{15}N$ values of bone collagen from infants and young children will be representative of a shorter dietary span (Waters-Rist and Katzenberg 2010). The $\delta^{13}C$ and $\delta^{15}N$ values of tooth dentine are a reflection of the diet during the time of tissue formation (Beaumont et al. 2013).

As taphonomic processes and post-depositional disturbances can affect the isotopic integrity of a sample, it is important to be informed about the archaeological context in which it was found. Certain indicators can be used to assess the quality of collagen after purification. For carbon and nitrogen stable isotope ratios in collagen and tooth dentin, a C/N ratio of 2.9–3.6, a wt%C above 30% and a wt%N above 11% are indicative of well-preserved collagen (Ambrose 1993;

DeNiro 1985; van Klinken 1999). Collagen yield has also been used as a collagen quality indicator, but the widespread use of ultrafilters to remove non-collagenous proteins and particles <30 kDa can reduce collagen yield by 50% or more (Müldner and Richards 2007).

Methods

Approximately 1.5 g of cortical bone from the long bones of the adults and long bones or ribs from subadults and the distal third of the root of the permanent first molar (0.2–0.3 g measured from the cemento-enamel junction, formation time between the ages of 5 and 9 years, Moorrees et al. 1963a; Smith 1991) were sampled for the stable isotope analysis (See Online Resource 1). A modified Longin method (Longin 1971) was used to extract collagen from the bone and dentine samples at the University of Otago, Dunedin, New Zealand (Brown et al. 1988; Collins and Galley 1998). Bone samples were cleaned with aluminium oxide air abrasive equipment (Bego Easyblast). A Dremel™ drill fitted with a diamond edge saw was used to cut the distal half of the root of the first molar (measured from the cemento-enamel junction). Similar to Fuller et al. (2003), the dentine was sampled horizontally rather than along growth increment lines for the purposes of attaining enough sample to analyse. Secondary dentine was removed from inside the pulp cavity of the tooth root with a Dremel™ drill fitted with a diamond burr. The samples of dentine were then sonicated for 5 min and fully dried.

All bone and dentine samples were soaked in 0.5 M HCl at 4 °C (changed every other day) until completely demineralized. The demineralized samples were then rinsed in deionized H_2O until they reached a neutral pH. The samples were gelatanized at 70 °C in a pH 3 solution for 48 h, followed by filtering with 5–8-μm Ezee® mesh filters (Elkay Laboratory Products) to remove any reflux-insoluble residues, and then ultrafiltered with Millipore Amicon Ultra 4 centrifugal filters (30,000 NMWL) to retain molecules larger than 30 kDa (Jacobi et al. 2006). The purified 'collagen' was frozen and then lyophilized for 48 h and subsequently weighed into tin capsules before analysis by EA-IRMS at Iso-Analytical (Cheshire, UK). Analytical error was routinely ±0.1‰ for $\delta^{13}C$ and ±0.2‰ for $\delta^{15}N$.

Levene's test for equality of variance was used before comparing means between two or more groups of data using parametric tests. Where there was no evidence of unequal variances ($p > 0.05$), two groups were analysed using a Student's t test. If the variances were not equal ($p < 0.05$), the unequal variance t test was used for the two groups.

There was evidence of widespread treponemal disease (yaws) within the cemetery sample (Buckley and Dias 2002; Buckley and Tayles 2003b), and, as yaws is a chronic disease, it is possible that the infection may have had an influence on the $\delta^{15}N$ values of individuals afflicted by the disease compared to the non-pathological individuals. Although only non-pathological bone was sampled for stable isotope analysis, adult individuals with 'probable' (gummatous lesions) and 'possible' (periostitis present on multiple limbs) lesions associated with treponemal disease (Table OR1) were still included in this study (Buckley and Tayles 2003b).

Results

Of the 146 bone samples and 92 tooth samples analysed in this study, four bone samples (burials 25, 36, 79 and 130) and six tooth samples (burials 73, 74, 84, 85, 87 and 195) did not reach the collagen quality indicators described above and were removed from the statistical analyses and interpretations (see Online Resource 1). One bone sample, from burial 1, displayed a %N of 10.9% (0.1% lower than the 11.0% cutoff) but adequate other collagen quality indicators, and it was therefore included in the current study.

Descriptive statistics of the isotope results of the bone collagen and tooth dentine samples for each demographic group in the Taumako skeletal sample are presented in Table 1. Results for Spearman's correlation between $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values and between $\delta^{13}C_{tooth}$ and $\delta^{15}N_{tooth}$ values are presented in Table 2.

The overall sample (n = 142) displayed average $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values of −16.5‰ ± 0.6 and 11.6‰ ± 1.2, respectively. When analysed by sex, males displayed similar $\delta^{13}C_{bone}$ values to females but significantly higher $\delta^{15}N_{bone}$ values compared with females (diff. 0.4‰, $p = 0.027$) (Fig. 3).

There was less than a 0.3‰ difference between the average adult $\delta^{13}C_{bone}$ value, the adolescent value, the juvenile value and the child value, but a slightly larger difference 0.5–0.6‰ between the average adult $\delta^{13}C_{bone}$ value and the infant and foetal/perinatal value (Fig. 3). When all the subadults were pooled into one group, a significant difference was observed between adult and subadult $\delta^{13}C_{bone}$ values (subadults 0.2‰ higher, $p = 0.023$). When the sexes were separated, the difference in adult and subadult $\delta^{13}C_{bone}$ values was only significant for the males (subadults 0.2‰ higher, $p = 0.048$) although the females also displayed a tendency for a difference in their $\delta^{13}C_{bone}$ values compared with that of the subadults (subadults 0.2‰ higher, $p = 0.057$). In the instances where the sample size of the subadult subgroup allowed for statistical analysis (≥10 individuals), significant differences were only observed between the $\delta^{13}C_{bone}$ values of the adults and the infant group (infants 0.5 ‰ higher, $p = 0.010$), but not the child or adolescent groups. This same trend was observable when the female and male $\delta^{13}C_{bone}$ values were compared with the $\delta^{13}C_{bone}$ values of these three subadult groups, respectively (infant higher than female, diff. 0.5‰, $p = 0.024$; infant higher than male, diff. 0.5‰, $p = 0.010$).

There was a larger range in the $\delta^{15}N_{bone}$ values (7.9–17.4‰) compared with the $\delta^{13}C_{bone}$ values (−18.6 to −14.4‰) in the Taumako sample (Fig. 4). Although the average adult $\delta^{15}N_{bone}$

Table 1 Summary stable isotope information for the Taumako skeletal sample

Group[a]	Bone collagen					Tooth dentine				
	n	$\delta^{13}C_{bone}$	± 1 SD	$\delta^{15}N_{bone}$	± 1 SD	*n*	$\delta^{13}C_{tooth}$	± 1 SD	$\delta^{15}N_{tooth}$	± 1 SD
Young males	24	−16.3	0.4	11.6	0.8	22	−16.6	0.6	11.4	0.7
Mid males	9	−16.7	0.6	11.7	0.9	9	−16.6	0.3	11.4	0.4
Old males	12	−16.4	0.6	11.8	1.1	6	−16.9	0.3	11.7	1.0
Total males	45	−16.4	0.5	11.7	0.9	37	−16.7	0.5	11.4	0.7
Young females	25	−16.6	0.5	11.1	0.9	25	−16.7	0.6	11.4	0.9
Mid females	15	−16.1	0.6	11.5	0.7	15	−16.6	0.4	11.3	0.4
Old females	9	−16.6	0.8	11.3	1.3	5	−16.6	0.1	11.3	0.7
Unknown age females	1	−16.5		11.5						
Total females	50	−16.4	0.6	11.3	0.9	45	−16.7	0.5	11.3	0.7
Unknown sex mid age	1	−16.2		11.8		1	−17.8		10.2	
Total adults	96	−16.4	0.6	11.5	0.9	83	−16.7	0.5	11.4	0.7
Adolescent (9.1–16.9 years)	10	−16.7	0.3	10.7	0.6	3	−16.9	0.5	11.6	0.3
Juvenile (5.1–9.0 years)	5	−16.6	0.3	11.1	0.8					
Young child (1.1–5.0* years)	14	−16.3	0.7	12.6	1.7					
Infant (0.1–1 year)	11	−16.9	0.5	12.5	1.4					
Foetal/perinatal (≤0)	5	−17.0	0.6	12.6	0.3					
Unknown subadult age	1	−17.0		11.2						
Total subadults	46	−16.6	0.6	12.0	1.5	3	−16.9	0.5	11.6	0.3
Total sample	142	−16.5	0.6	11.6	1.2	86	−16.7	0.5	11.4	0.7

*no subadults aged 3.1−5.0 years were found

[a] *YA* Young adult (17−34 years), *MA* Mid adult (35−49 years), *OA* Old adult (50 + years), *UK* unknown age

value was 0.8‰ higher than the average adolescent value (and 0.4‰ higher than the juvenile value), it was ≥1.0 lower than the average young child, infant and foetal/perinatal $\delta^{15}N_{bone}$ values (Fig. 3). When all the subadults were pooled into one group, a significant difference was observed between adult and subadult $\delta^{15}N_{bone}$ values (subadults 0.5‰ higher, $p = 0.029$). When the sexes were separated, the differences in adult and subadult $\delta^{15}N_{bone}$ values were significant for the females (subadults 0.7‰ higher, $p = 0.005$) but not the males (subadults 0.3‰ higher). In the instances where the sample size of the subadult group allowed for statistical analysis (≥10 individuals), significant differences were observed between the $\delta^{15}N_{bone}$ values of the adults and the infant group (infants 1.0 ‰ higher, $p = 0.033$), the young child group (young child 1.1 ‰ higher, $p < 0.001$) and the adolescent group (adolescent 0.8 ‰ lower, $p = 0.002$). This trend was observable when the average female (infant 0.8‰ higher, $p = 0.024$; young child 1.3‰ higher, $p < 0.001$; adolescent 0.6‰ lower, $p = 0.018$) and male (infant 0.8‰ higher,

Table 2 Spearman's correlation between $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values and $\delta^{13}C_{tooth}$ and $\delta^{15}N_{tooth}$ values

Group	Bone collagen				Tooth dentine	
	n	r^2	*p*	*n*	r^2	*p*
Males	45	0.502	<0.001	37	0.383	0.019
Females	50	0.599	<0.001	45	0.562	<0.001
Total adults	96[a]	0.541	<0.001	83	0.493	<0.001
9.1–16.9	10	−0.115	0.751	3	N/A	N/A
5.1–9.0	5	N/A	N/A	3	N/A	N/A
1.1–5	14	0.350	0.220			
0–1	11	−0.264	0.433			
<0	5	N/A	N/A			
Total subadults	46[a]	0.058	0.702			
Total sample	142[a]	0.327	<0.001	86	0.464	<0.001

[a] Total samples include unaged and unsexed individuals

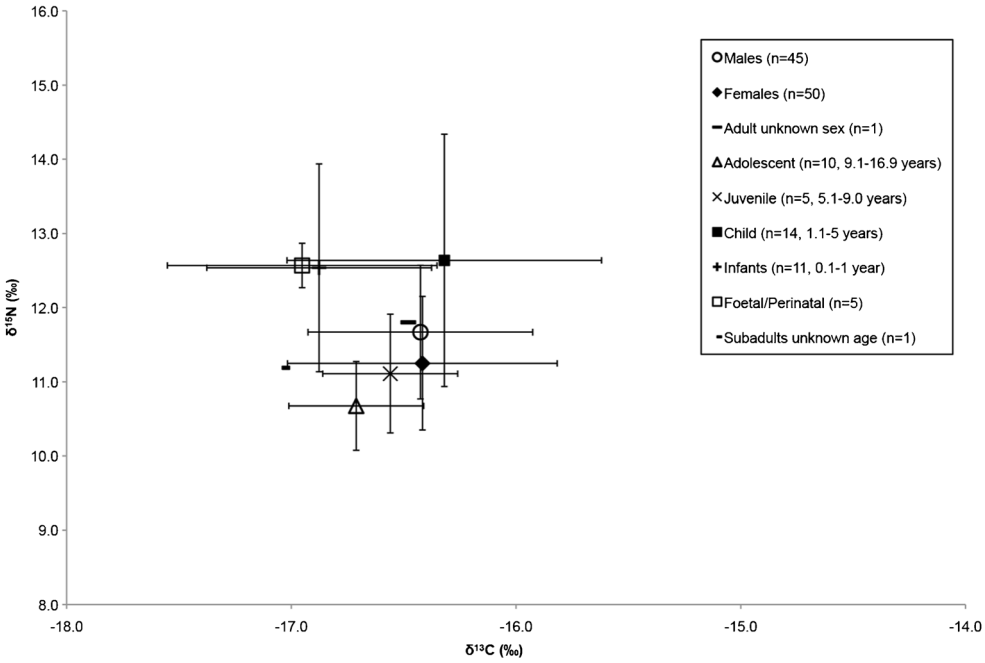

Fig. 3 Comparison of mean (± 1 SD) $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values plotted by age cohort and sex

$p = 0.016$; young child 0.9‰ higher, $p = 0.008$; adolescent 1.0‰ lower, $p < 0.001$) $\delta^{15}N_{bone}$ values were compared to those of each subadult subgroup.

Teeth were mainly sampled from adults ($n = 83$), but three adolescents were also sampled. The overall sample ($n = 86$) displayed a range in $\delta^{13}C_{tooth}$ and $\delta^{15}N_{tooth}$ values of −17.9 to −15.0 and 9.8 to 14.0‰, respectively (Fig. 4). When analysed by sex, males displayed similar $\delta^{13}C_{tooth}$ and $\delta^{15}N_{tooth}$ values with females. The adolescent $\delta^{13}C_{tooth}$ values were slightly lower (0.2‰) and $\delta^{15}N_{tooth}$ values slightly higher (0.2‰) compared with the adult $\delta^{13}C_{tooth}$ values.

A significant difference was observed between the $\delta^{13}C_{bone}$ and $\delta^{13}C_{tooth}$ values for all the adults (teeth 0.3‰ higher, $p = 0.002$), the males (teeth 0.3‰ higher, $p = 0.034$) and the females (teeth 0.3‰ higher, $p = 0.048$). No significant differences were observed between the $\delta^{15}N_{bone}$ and $\delta^{15}N_{tooth}$ values for the overall sample of adults (bone 0.1‰ higher), the males (bone 0.3‰ higher) or the females (no difference). Overall, the average adult $\delta^{15}N_{tooth}$ value was 0.3‰ higher than the average $\delta^{15}N_{bone}$ value of the juveniles aged 5–9 years and the average adult $\delta^{13}C_{tooth}$ value was 0.1‰ higher than the juvenile $\delta^{13}C_{bone}$ value (Fig. 4). For the adolescents, their average $\delta^{13}C_{tooth}$ value was 0.2‰ lower than their average $\delta^{13}C_{bone}$ value and their $\delta^{15}N_{tooth}$ value was 0.9‰ higher than their average $\delta^{15}N_{bone}$ value (Fig. 4).

To address this potential influence of treponemal disease on adult $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values, a regression equation was used to assess if there was evidence of a difference between the stable isotope values of adult individuals with possible and probable treponemal lesions and the other 'normal', non-pathological individuals. There was no evidence of an overall difference in $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values between the probable and possible pathological and non-diseased individuals.

Discussion

The diet of the adult, adolescent and juvenile individuals can be understood by comparing their $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values with a Pacific island dietary baseline developed from the isotopic ratios of modern plants and animals and prehistoric fauna (Fig. 5) (for a complete discussion of the dietary baseline, see Kinaston et al. 2014b). The average $\delta^{13}C$ value (−19.9‰ ± 0.5) of the fruit bat bones represents a purely C_3 terrestrial-based diet, which corresponds with the $\delta^{13}C$ value of −20.0‰ that other studies have reported as representing a C_3 terrestrial-based diet in the Pacific islands (Richards et al. 2009; Valentin et al. 2006). Taking into account the trophic effect of 0–2‰ for the human $\delta^{13}C_{bone}$ values and 2–4‰ for the $\delta^{15}N_{bone}$ values so the human bone collagen can be directly compared to the faunal bone collagen values, the protein portion of the human diet likely consisted of marine foods from reef and pelagic sources, including turtles and possibly seabirds, horticultural and arboricultural plant foods and terrestrial animals (most likely domesticated species) (Fig. 5). The significant positive correlation between the $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values supports this interpretation, and the differences between the individuals (from the adult, adolescent and juvenile age cohorts only) were likely a result of differing proportions of the same types of marine protein and lower trophic level terrestrial foods (such as starchy root vegetables

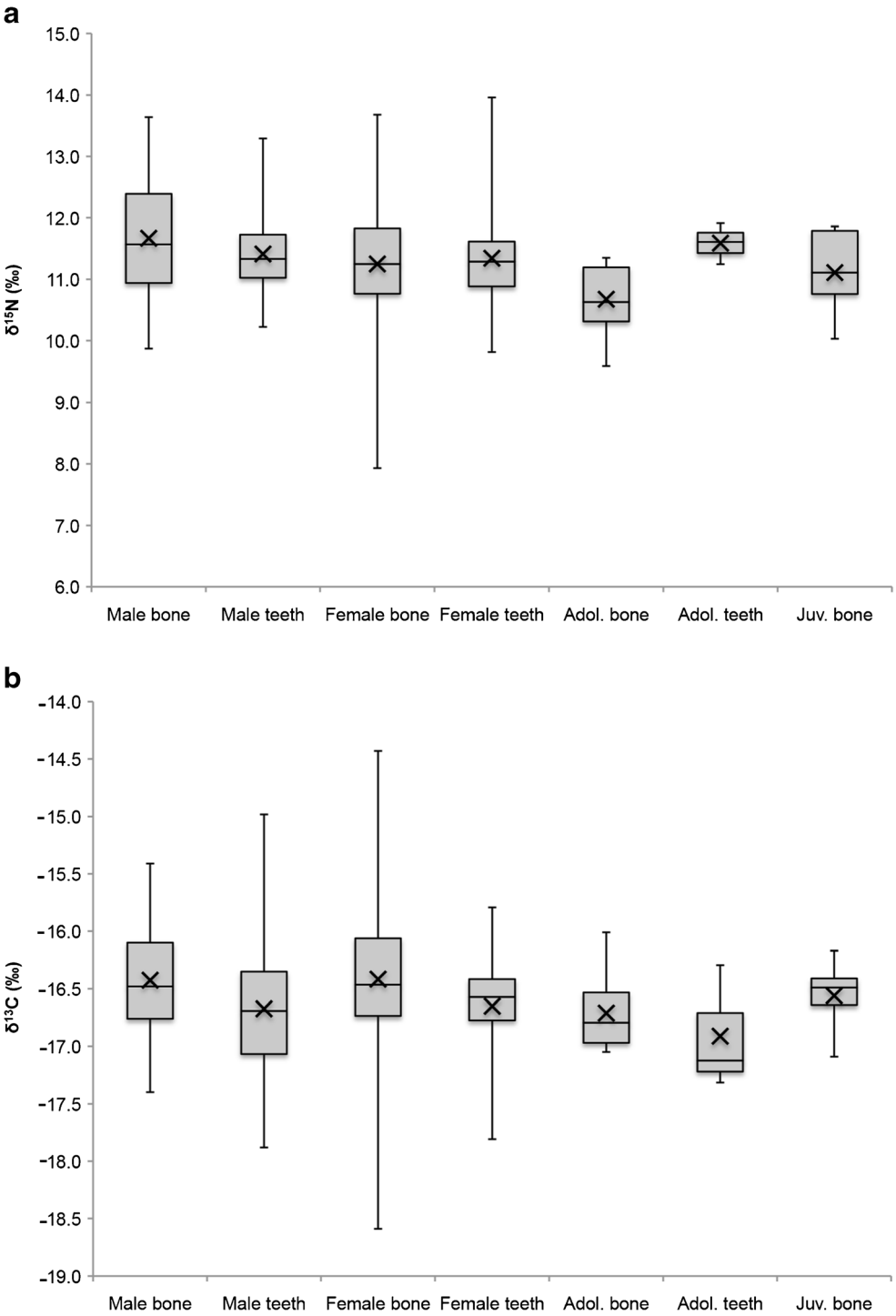

Fig. 4 *Box plots* comparing the median (*line*), mean (*x*), minimum (*lower error bar*), and maximum (*upper error bars*) $\delta^{15}N_{bone}$ and $\delta^{15}N_{tooth}$ values (**a**) and $\delta^{13}C_{bone}$ and $\delta^{13}C_{tooth}$ values (**b**) plotted by age cohort and sex

and nuts) (Kinaston et al. 2013a; Richards and Hedges 1999). These findings mirror those of the previous isotopic study of the adult individuals from Taumako, and a comprehensive discussion of diet on Taumako, including sex- and status-related differences, is presented in Kinaston et al. (2013a). The following interpretations will focus on the isotopic differences between the age groups and tissue types (bone and teeth) to provide a more nuanced understanding of age-related differences in diet at the site and information regarding survivorship and stress in the Taumako sample.

The significant difference observed between the male and female $\delta^{15}N_{bone}$ values was not observed in their $\delta^{13}C_{tooth}$ or $\delta^{15}N_{tooth}$ values (Fig. 4). This pattern suggests that the variation in adult diet that exists between the sexes was not present during

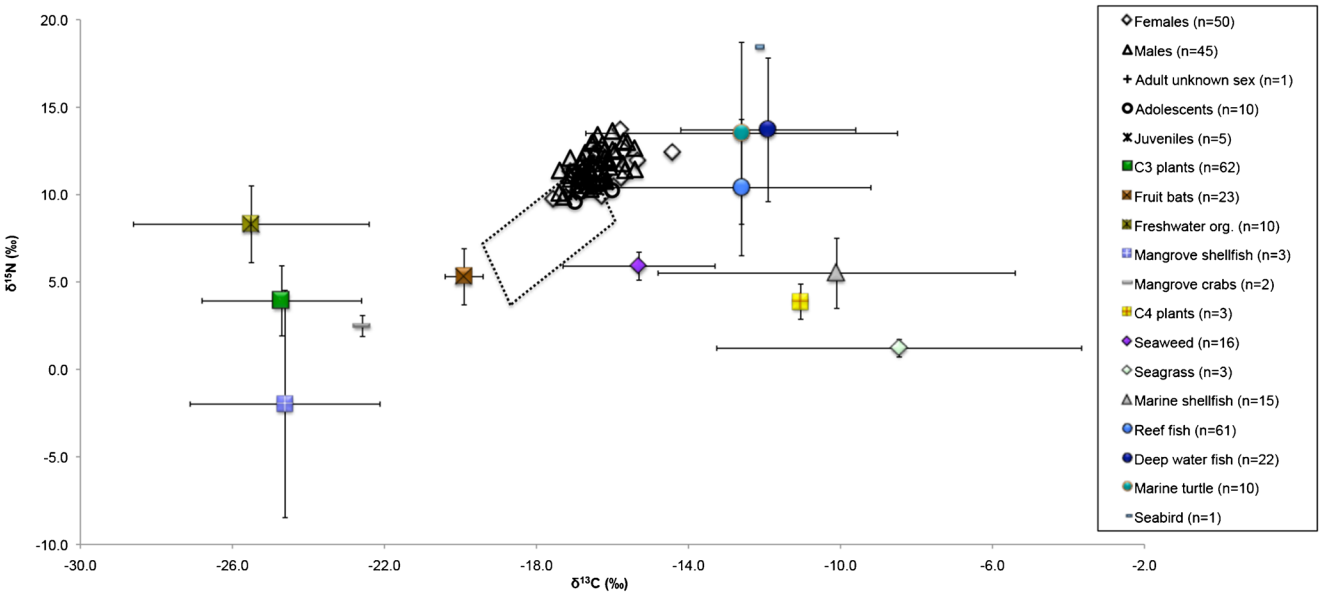

Fig. 5 $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values of the Taumako individuals in reference to a Pacific Island dietary baseline (from Kinaston et al. 2014b). The *dotted lines* delineate the possible protein diet after correction for the trophic effect. The fruit bat bone collagen values represent a 100% terrestrial C_3 diet

the time of tooth formation of the dentine samples (i.e. 5–9 years). The differences in bone and tooth stable isotope values may suggest that, during the ages of 5–9 years, these individuals consumed slightly more terrestrial food and less marine and, possibly, less C_4 plants than in their later lives.

The adolescent $\delta^{13}C_{bone}$ and $\delta^{13}C_{tooth}$ values follow a similar trend as the adults, but their $\delta^{15}N_{tooth}$ values were higher than their $\delta^{15}N_{bone}$ values. This pattern suggests that the diet of the adolescents changed from the time that they were juveniles, specifically that they were eating lower trophic level foods when they died. Alternatively, the higher adolescent $\delta^{15}N_{tooth}$ values coupled with low $\delta^{13}C_{tooth}$ values may suggest that these individuals experienced some type of stress during the time of tooth development (discussed further below) and this may have affected their survival (Beaumont et al. 2015). The juvenile and the adolescent $\delta^{15}N_{bone}$ values were lower than the adult values, and this was statistically significant for the adolescent group (Figs. 3 and 4). The trend at Taumako suggests that the adolescent and to a lesser extent juvenile individuals ate protein from lower trophic levels than the adults, especially the males. This pattern may indicate that diet played a role in survivorship or possibly that unwell individuals may have been fed differently. Animal flesh, especially from turtle and pelagic species of fish, pig and chicken, is considered 'high-status' food in the Pacific islands. As discussed in detail in Kinaston et al. (2013a), the adult male individuals may have had more access to these higher-status foods compared to females and, with the addition of these new data, the juvenile and adolescent individuals at the site. Although there are usually set mealtimes, people (especially children) snack throughout the day in modern non-urban Pacific island communities (Barrau 1958; Barrau 1961; Kirch 2002; Oomen and Malcolm 1958). A higher proportion of lower trophic level foods foraged from the land and inshore environment for snacks, such as nuts, fruits, freshwater organisms, insects, shellfish, crustacea and seaweed, may have also influenced the observed values of the Taumako subadults.

In a palaeodietary study of a skeletal sample from Medieval Kulubnarti, Sudanese Nubia, Turner et al. (2007:18) suggested that variation in adult and subadult $\delta^{13}C$ and $\delta^{15}N$ values 'could be attributed to a number of possible factors, including differential growth rates or stress episodes, differential dietary intake and variable levels of water stress'. The effect of potential water stress elevating the $\delta^{15}N$ values of any member of the sample can be ruled out at Taumako as the annual rainfall in the region is 5598 mm and the environment is extremely humid. With regard to the effect of growth on stable isotope values of subadults, Waters-Rist and Katzenberg (2010) analysed the $\delta^{15}N$ values of the diaphyses, metaphyses and epiphyses of a number of subadult individuals and found no significant differences between these areas of growing bones, thus supporting the suggestion that growth had no effect on $\delta^{15}N$ values. As will be discussed further below, increased stress and disease would likely result in higher, not lower, subadult $\delta^{15}N$ values (Beaumont et al. 2015; Katzenberg and Lovell 1999), and it is therefore suggested that age-related dietary variation is a likely reason for the difference observed between the adult, adolescent and juvenile $\delta^{15}N_{bone}$ values, rather than stress. The subadult individuals were the non-survivors and are therefore less representative of the living population than the adults. The possible dietary differences could actually represent the subsistence strategies, along with other factors affecting health, that 'failed' and subsequently affected the survivorship of these individuals (Turner et al. 2007).

The $\delta^{13}C_{bone}$ values of the foetal/perinatal, infant and, to a smaller extent, young child individuals were lower than the average adult female $\delta^{13}C_{bone}$ value (Fig. 6). The trophic effect for $\delta^{13}C$ values is suggested as 0–2‰, and therefore, the infants and young children that were breastfed should theoretically display elevated $\delta^{13}C_{bone}$ values compared to the adult female mean. The elevated $\delta^{15}N_{bone}$ values of some of the infants and young children compared to the average female $\delta^{15}N_{bone}$ value, especially those outside the one standard deviation of the female mean, may be a result of the trophic effect of breastfeeding (Fuller et al. 2006a; Fuller et al. 2006b; Jay 2009) (Fig. 6). However, few infant or young child individuals fall outside the 2‰ suggested as a low value for trophic level enrichment of ^{15}N in bone collagen. The lack of 3.1 to 5-year-old individuals for comparison with these younger individuals means that it is impossible to determine if the $\delta^{15}N_{bone}$ value would be lower in this older subadult age cohort. There was a large range in $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values of the foetal/perinatal and young infant individuals compared to the adult female mean values. As a result of the observed variation in stable isotope values of the foetal/perinatal individuals and very young infants, in addition to the uneven demographic profile (i.e. lack of 3–5-year-olds) of the sample, it is difficult to estimate the duration of breastfeeding and the types of weaning foods for the Taumako sample based on the current data set. However, the large range in $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values of the foetal/perinatal and young infant individuals compared to the adult female mean values supports the suggestion that there are other possible explanations for the elevated young subadult $\delta^{15}N_{bone}$ values.

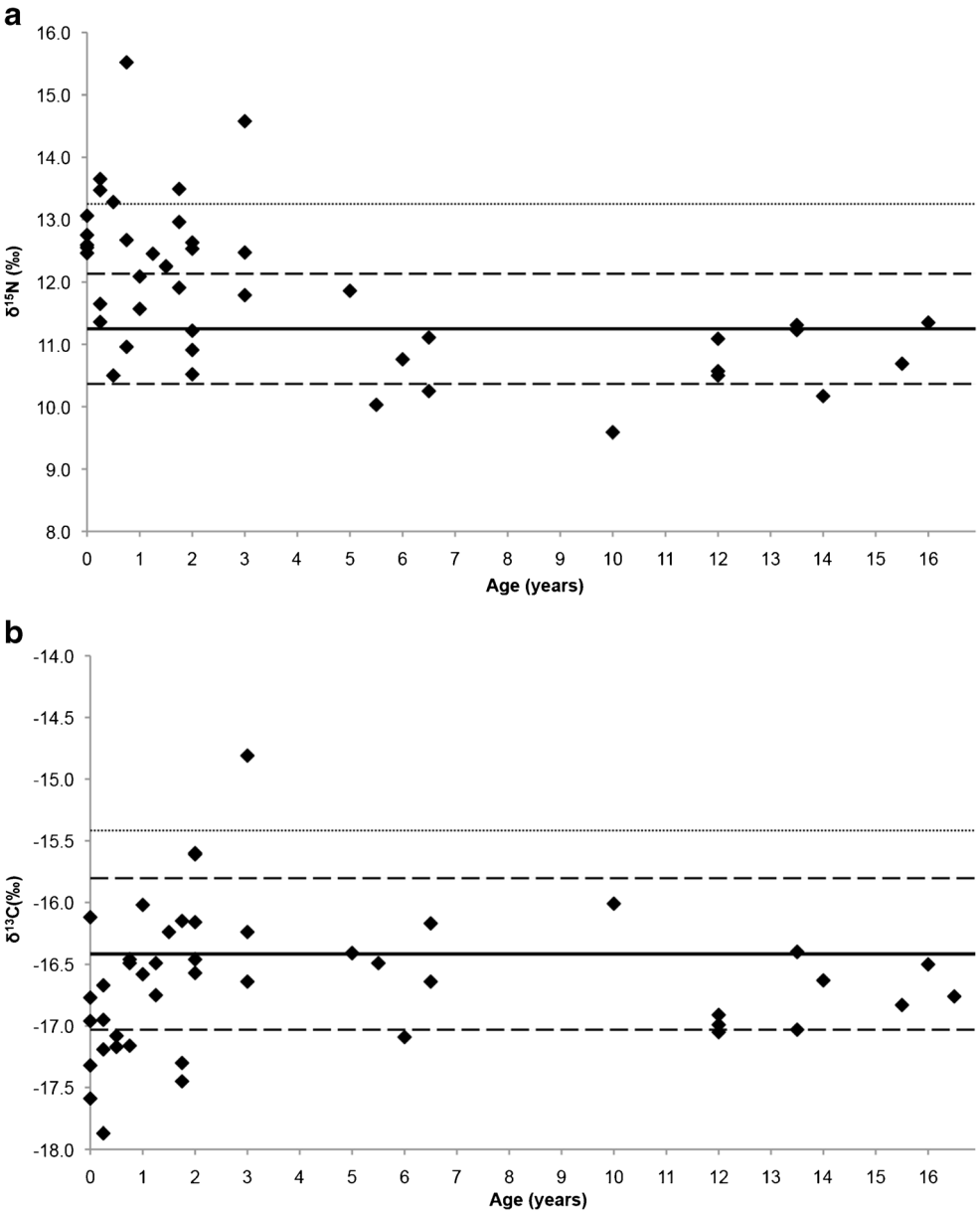

Fig. 6 Subadult $\delta^{15}N_{bone}$ (**a**) and $\delta^{13}C_{bone}$ (**b**) values in reference to the adult female mean (*solid line*) ± 1 SD (*dashed line*), in addition to low known values for the trophic effect (2.0 ‰ for $\delta^{15}N$ and 1.0‰ for $\delta^{13}C$, *dotted lines*)

The fact that even the foetal/perinatal individuals displayed elevated $\delta^{15}N_{bone}$ values compared to the adult female mean (Fig. 6) may suggest that some other factors influenced their isotopic values as these very young individuals would not have had time to incorporate a breastfeeding signal in their tissues before death. A modern study of hair from mothers and their newborns showed a strong correlation between the $\delta^{15}N$ values of mother/infant hair, and the $\delta^{15}N$ and $\delta^{13}C$ values of the infants' hair were statistically significantly higher than that of their mothers (de Luca et al. 2012). As such, the de Luca et al. (2012) study indicates that certain physiological effects of pregnancy may act to raise foetal tissue $\delta^{15}N$ and $\delta^{13}C$ values, but it is unknown if this enrichment is applicable to bone collagen. A recent study conducted by Beaumont et al. (2015) found marked differences between the $\delta^{15}N$ and $\delta^{13}C$ values of child and adult individuals from high-resolution samples of dentine. From these results, they suggested that stress and ill health during pregnancy and childhood may have affected the stable isotope values of the non-survivors. They concluded that the interpretation of breastfeeding patterns from bone collagen values (as attempted in this study) does not account for the complexities linked to the physiological status of pregnant mothers, their young offspring and the children in a sample population who died for unknown reasons. In our study, the low $\delta^{13}C_{bone}$ values of the infant and young child individuals compared to the adult female mean could further support that the model used to investigate

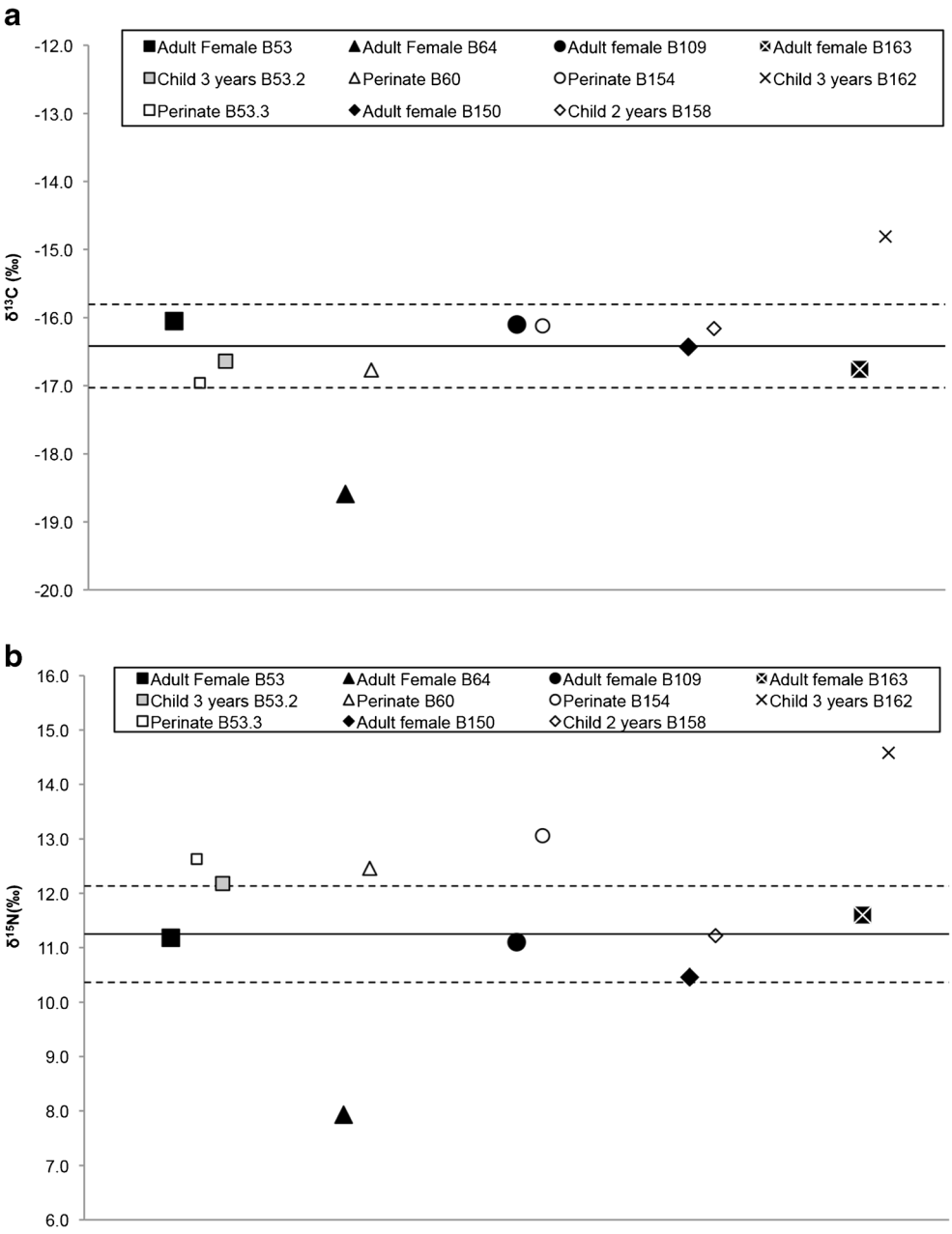

Fig. 7 $\delta^{13}C_{bone}$ (**a**) and $\delta^{15}N_{bone}$ (**b**) values for the adult female and subadult multiple and co-interments compared with the overall adult female mean stable isotope values (*solid line*) ± 1 SD (*dashed line*)

breastfeeding patterns in this study may not be correct. At the prehistoric Teouma site in Vanuatu, a similar trend was found (elevated foetal/perinatal $\delta^{15}N_{bone}$ values and lower $\delta^{13}C_{bone}$ values compared with the adult female mean) and it was suggested that this pattern could be indicative of possible maternal ill health and in utero stress (Kinaston et al. 2009). The same pattern of elevated foetal/perinatal $\delta^{15}N_{bone}$ values can be observed when the adult female and subadult co-interments are compared (Fig. 7), although the $\delta^{13}C_{bone}$ values of the foetal/perinatal individuals are more comparable with those of their co-interred adult female. As suggested by Beaumont et al. (2015), the foetal/neonatal bone collagen could be an indicator of the mother's diet and physiology during the time of pregnancy. By comparing the stable isotope values of these foetal/neonatal individuals with the females' mean, the health and dietary of the pregnant mothers in a sample may possibly be assessed (Beaumont et al. 2015).

Taumako island is located in a region of high malaria endemicity, a pathogen known to cause significant ill health, particularly in pregnant women and young infants (Hendrickse 1987). Malaria and other pathogens are known to have influenced the expression of non-specific health indicators such as cribra orbitalia and dental enamel defects (Gowland and Western 2012). Both of these indicators of stress were found in high frequencies in the Taumako population in previous research, particularly affecting children in higher frequencies and with greater severity than adults (Buckley 2016; Buckley 2006). Another specific infectious disease that may have influenced in utero stress is widespread treponemal disease, yaws (*T. pertenue*) in the sample (Buckley 2016; Buckley and Tayles 2003a). Out of 44 individuals with cranial and postcranial lesions, 20 individuals (45.5%) were diagnosed with probable treponemal disease based on the presence of gummatous lesions pathognomonic of the disease. A further six individuals were suggested as having possible treponemal disease based on the presence of osteoblastic lesions in the tibia and two other limb bones (Buckley and Tayles 2003b). Disease has been suggested as a possible cause of variation in $\delta^{15}N$ values, typically resulting in enrichment rather than depletion in ^{15}N (Katzenberg 1999; Katzenberg and Lovell 1999; White and Armelagos 1997). This study found no differences between the $\delta^{13}C_{bone}$ and $\delta^{15}N_{bone}$ values of the probable and possible pathological and non-diseased individuals. However, of the females who were represented in the multiple and co-interments, burials 53, 64 and 150 all displayed pathognomic lesions indicative of treponemal disease (i.e. probable yaws) and burial 109 was diagnosed with possible yaws following the criteria presented in Buckley and Tayles (2003b). The other female co-interment, burial 163, did not display any periosteal lesions on her postcranial remains, but did display evidence for cribra orbitalia, a non-specific indicator of stress (Buckley 2016). All but one (burial 60) of the subadult co-interments also displayed evidence of stress in the form of endocranial new bone formation (burials 53.2 and 162), cribra orbitalia (burials 53.3 and 162) and periosteal reactions on the post-cranial bones (154 and 158)(Fig. 7). It is possible that the treponemal disease of three, possibly four, of the females and other, as yet unidentified stressors (e.g. malaria, hookworm), may have negatively affected the health of their foetus (as evidenced from the non-specific indicators of stress) and the ultimate survival of their offspring. The high pathogen loads affecting the health of the population, as expressed in the skeletal record, may have affected the higher $\delta^{15}N$ values of the subadult multiple and co-interments and other young individuals in the sample.

Conclusions

Stable isotope analysis has provided an avenue to address specific questions about the lives of people who were interred in the Namu burial ground on Taumako. There were few faunal remains excavated from the Namu burial ground, and no other methods, such as microfossil or palynological analyses, were previously used to try to ascertain dietary patterns at the site. The isotopic analyses performed here have offered a way to understand the diet of the population interred in the Namu burial ground, and because this method uses the individual as the unit of analysis, more nuanced information regarding the childhood diet of the adults (the survivors) and subadults (the non-survivors) and its potential effect on survivorship could be better understood. It was found that juveniles and adolescents who did not survive were eating foods from lower trophic levels than the adults, especially the males, and this may have affected their survival. The difference in diet found between the adult males and females were not observed when these individuals' teeth were analysed, indicating that the consumption of higher trophic level foods known to be more 'valuable' in the Pacific (i.e. meat and fish) by males started sometime after the formation of the distal half of the first molar (after 9 years old) and has highlighted a hitherto unknown change in dietary patterns between different life stages in this past population. It was difficult to draw conclusions regarding the duration of breastfeeding and timing of weaning using the stable isotope results from the Taumako neonates, infants and young children because of the variation in stable isotope values of these young individuals and the demographic profile of the sample (a lack of 3.1 to 5-year-old individuals). The foetal and neonatal individuals who were too young to display a breastfeeding signal in their bone collagen displayed high nitrogen stable isotope values compared to the adult females' mean, and it was therefore suggested that other factors, such as physiological stress from disease during pregnancy, may have influenced the nitrogen stable isotope values of all the foetal, infant and young subadults who died.

Recent studies have started questioning the validity of stable isotope values of the bone collagen of subadults because of

the possible effect of stress on their $\delta^{13}C$ and $\delta^{15}N$ values. High-resolution microsampling of tooth dentine of adults (i.e. the survivors) can help determine the possible reasons for variable $\delta^{13}C$ and $\delta^{15}N$ values within a sample population (Beaumont et al. 2015). In this study, the use of bulk tooth dentine to assess the childhood diet of the adults may therefore be more representative of the true diet of these young individuals, as compared to the bone collagen values of the deceased subadults (Wood et al. 1992). Future analyses of the Taumako population will use high-resolution microsampling of tooth dentine to assess the diet and health of these individuals.

Our approach has provided insight into human behaviour, cultural processes and health at the Taumako site, such as possible culturally moderated feeding practices and labour specialization that may have affected diet, nutrition and survival. Focussing on groups that have traditionally been overlooked, especially women, infants and children, can help us understand the quality of life of all members of a past community. It is suggested that future studies may benefit from using isotopic data to help address health and disease questions in this and other samples.

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