Diet and subsistence in Remote Oceania: an analysis using oral indicators of diet

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Abstract: This chapter analyzes oral conditions (caries, periapical cavities, ante-mortem tooth loss, periodontal disease, chipping, and dental wear) in order to understand dietary patterns in prehistoric Remote Oceania. Three prehistoric cemetery samples from Tonga, Fiji, and the Cook Islands are analyzed to examine dietary differences at intra-population and inter-population levels that may be related to variations in subsistence practices or other cultural influences. Discrepancies between the results from oral conditions analysis and previous isotopic analyses are discussed.

Examining diet and subsistence patterns of prehistoric humans are especially important in Remote Oceania, where the generally ecologically sparse islands predicated the need for human-moderated colonizing adaptations in order for settlements to thrive. While Near Oceania (Figure 1) is home to numerous species of mammals, land birds, and terrestrial flora, there is a sharp decline in ecological biodiversity as one continues eastwards into Remote Oceania (Steadman 2006; Stoddart 1992). When Austronesian-speaking people arrived in Remote Oceania around 1,350 BCE (Denham et al. 2012; Kirch 1997; Spriggs 1997), they brought with them a transplanted landscape of root vegetables, tree crops, and animal domesticates that was integral to the human subsistence systems (Kennett et al. 2006).

Prehistoric diet in Remote Oceania would have typically included farinaceous plant staples, such as taro (*Colocasia esculenta*), yam (*Dioscorea spp.*), and breadfruit (*Artocarpus altilis*), which were supplemented by meat from animal domesticates such as pigs (*Sus scrofa*), dogs (*Canis familiaris*), and chickens (*Gallus gallus*) in addition to marine resources (Jones 2009; Jones and Quinn 2009; Szabó and Amesbury 2011). However, regional variations in diet probably existed because of ecological and cultural differences between islands. This study's analysis of three cemetery samples (Bourewa in Fiji, 'Atele in Tonga, Western Polynesia, and Rima Rau, Cook Islands, Eastern Polynesia) provides the opportunity to characterize and compare diet and subsistence practices in different areas of Remote Oceania during the late prehistoric/protohistoric period (c. 1,200 – 1,800 CE).

Reconstructing the diet and subsistence of past peoples using macroscopic examinations of teeth and the surrounding bony structures is a common approach in bioarchaeology (Hillson 1979; Larsen et al. 1991; Lukacs 2012). Oral health interpretations of diet can be compared to the results of isotopic analyses previously conducted on two of the three sites (Stantis et al. in prep-a; Stantis et al. in prep-b). Dietary isotopic analyses (δ^{15}N and δ^{13}C in this study) provide a direct method of determining proportions of types of food eaten by an individual and are a valuable tool in understanding dietary patterns between and within sites (Ambrose and Krigbaum 2003; Katzenberg 2007; Schoeninger 2010).

This is the first study to synthesize isotopic and oral indicators of diet and compare Fijian and Polynesian diet using these lines of evidence. There are no faunal remains or other archaeological evidence of diet and subsistence associated with any of the skeletal assemblages examined in this chapter (Davidson 1969; Nunn et al. 2004) and so bioarchaeological investigations of diet provide the only line of evidence for subsistence and diet at these sites.

Three aims are addressed in this chapter. First, we aim to examine inter-site and intra-site differences in the prevalence of oral conditions between these three pre-/proto-historic Pacific populations (Table 1) and isotopic compositions between two of the three assemblages. Second, we aim to examine the relationship between the isotopic and oral conditions data to assess whether the oral conditions are a result of dietary differences that may be related to island-specific subsistence practices. Finally, our third aim is to assess any sex-related differences in the frequencies of oral conditions and isotopic values that may be related to culturally-proscribed dietary patterns or biological/hormonal differences.

We hypothesize that there will be few significant differences in diet between the three populations, as Remote Oceania diets largely consist of the same proportions of foods: root vegetables supplemented with marine resources and some terrestrial animals. Our second hypothesis is that the two methods of assessing diet (oral indicators of diet and isotopic analyses) will agree. Our final hypothesis is that there will be significant dietary differences between the males and females as evidenced by oral conditions.

BACKGROUND

Polynesia and Fiji

Polynesia can be divided into two broad regions: Western and Eastern (Figure 1). The core of Western Polynesia, Tonga and Samoa, were the first Polynesian islands inhabited by humans around 850 BCE (Burley et al. 2012; Leach and Green 1989). Although Eastern and Western Polynesia share a common genetic and linguistic background, distinct cultural differences regarding aspects of religion, social structure, and material culture are present along the Eastern-Western division (Bellwood 1987; Burrows 1938; Kirch 2000).

Fiji was settled around the same time as Tonga and Samoa (Nunn and Petchey 2013). Due to their geographic proximity, the cultures of Fiji, Tonga, and Samoa are inexorably linked. However, researchers have a difficult time placing Fiji in a simple cultural classification. Few researchers place Fiji within Western Polynesia, as distinctive cultural influences from the western Pacific islands came to Fiji around 250 BCE that never reached Tonga and Samoa (Burley 2013; Green 1995). Fiji is commonly grouped with Western Polynesia in archaeological research (2008; Burley and Clark 2003; Davidson 1977). While being mindful of the issues around geographic labels in this complex region we will henceforth refer to the region where all three sites are located as eastern Remote Oceania.

The ecological and archaeological context of samples analysed

‘Atele, Tongatapu, Tonga

The Kingdom of Tonga is an archipelago composed of two parallel, geologically distinct island chains measuring 748 km^2 altogether. The western arc island chain, the Tongan Volcanic Arc, is comprised of high islands with little to no coral reef formation. The lack of reefs greatly reduces the amount of marine life available around these islands. The eastern island chain is non-volcanic and largely composed of uplifted coral limestone. Barrier reefs surround these islands, creating resource-rich marine environments which the local populations have been utilizing for centuries (Nunn 1998; Taylor and Bloom 1977). Tephra from the volcanic islands periodically falls on the eastern islands, providing good quality soil for horticultural pursuits. As a result of the horticultural potential and rich marine environment available for exploitation, the eastern islands have been the core of Tongan settlement since Lapita colonization (Burley 1998).

Tongatapu is the largest island in the eastern chain of the kingdom, with an area of approximately 250 km^2. A typical eastern island geologically, it is composed of coral limestone and covered in volcanic soil (Dickinson 2006). Like most of the southern islands in the archipelago, Tongatapu is flat with a maximum elevation of 65 m on the southeastern coast that gently descends into sandy beaches and mangrove forests on the northern side of the island (Nunn 1998; Taylor and Bloom 1977).

In 1964, Janet Davidson led an excavation of two burial mounds at ‘Atele on the island of Tongatapu (Davidson 1969). Using the Tongan mound classification system created by McKern (1929), the two mounds may be the burial places of two different social classes: To-At-1, the relatively shallow mound (80 cm at its highest), would be classified as a *tanuanga*, or commoner’s mound; To-At-2, the taller mound (2.5 m high) with a shallow encircling ditch, would be a *fa’itoka*, or burial mound for the lesser chiefs and their retainers. Typically the disturbance of the dead is *tapu* (taboo) on Tonga. However, at the time of the excavation there was no living memory of the people buried in the ‘Atele mounds and thus excavation was permitted. The main research focus of the original excavations was the method of mound construction and types of mound use, whether for commoner or chiefly burial. As such, neither mound was fully excavated; trenches to the centers and on edges of the mounds were dug instead. Only 2.9% and 13.6% of the possible mound areas were excavated for To-At-1 and To-At-2, respectively. No grave goods were found in either mound although staining of the skeletal material may have been a result of the wrapping of the corpses in *tapa*, or woven cloth.

To date no research has found evidence that the two mounds interred individuals of different social status; Davidson (1969) found no differences between the mounds in the method of interment or mound construction, and bioarchaeological research focusing on health and activity found no differences between the individuals placed in these mounds (Buckley 2001; Foster

2011; Pietrusewsky 1969). Understanding possible intra-site differences in diet between the two mounds is important before treating To-At-1 and To-At-2 as a homogenous representation of the Chiefdom Period in Tonga, a time when the Tongan maritime empire controlled the trade of prestige goods in a series of inter-island networks throughout much of Remote Oceania (Kirch 2000).

Radiocarbon dating conducted in the 1960s placed the ‘Atele mounds in the Formative Period (400 – 1,200 CE). Recent uncorrected AMS radiocarbon dates from human bone places the time period of interment more recently between 1,450 – 1,750 CE. Although there seems to be a longer span of use in the To-At-1 mound (1,460 – 1,670 ± 20 CE) compared to the To-At-2 mound (1,670 – 1,730± 20 CE), the entire population is treated as a single series for this study. The recent radiocarbon dates show that all the individuals interred in the ‘Atele burial mounds are from the Chiefdom Period. Although some of these dates may overlap with European contact (c. 1,800 CE), there is no evidence of European materials in the burial context. The assemblage (*n* = 126) is relatively complete. Some instances of intercutting of burials during mound use and reburial of disturbed bone left some individuals incomplete. As such, 89 individuals had cranial material for the examination of oral conditions.

Bourewa, Fiji

Fiji consists of around 330 islands, 90 of which are currently occupied by humans. Altogether, the Fijian landmass totals 18,272 km^2 and Viti Levu is the largest island in Fiji measuring 10,388 km^2. With a maximum elevation of 1,394 m the landscape of Viti Levu is described by some as “rugged rather than mountainous” (Anderson and Clark 2009:2). In contrast to the smaller islands included in this study, Viti Levu's large size, variable rainfall, and geological complexity creates highly varied ecosystems.

The archaeological site of Bourewa is located on the southwest coast of Viti Levu and was excavated over seven field seasons beginning in 2003 (Nunn et al. 2004; Nunn and Petchey 2013). The lowest layers of the site contain what is perhaps the oldest-known Lapita settlement in Fiji; radiocarbon dating of shell and charcoal from the lowest layers establish settlement at Bourewa by 866 cal. BCE (Nunn and Petchey 2013). Sixteen burials from a later period were cut into the Lapita occupation at Bourewa and are roughly contemporaneous with the construction of the ‘Atele burial mounds (1,200 – 1,950 cal. CE). Although ceramic, stone, and shell artifacts were recovered from the deeper layers, no apparent grave goods were associated with the burials (Nunn 2007). Completeness of the burials from Bourewa was variable; some skeletons were nearly complete with little post-mortem damage, while others were incomplete as a result of post-depositional disturbance from plowing. Twenty-four individuals had cranial material for the examination of oral conditions.

Rima Rau, Cook Islands

The Cook Islands are an archipelago that consists of 15 major islands distinguished by two distinct island types: the older Northern Islands, composed of ecologically precarious coral atolls with little fertile soil or fresh water and the younger Southern Islands which tend to be *makatea* (uplifted coral reef) or high islands, with fertile, wet lowlands and mountainous centers, surrounded by a fringing coral reef (Marshall 1930). The island of Atiu is a *makatea* island in the Southern Island chain, located approximately 215 km northeast of Rarotonga, the main island of the Cook Islands archipelago (Stoddart et al. 1990). Atiu is the smallest island in the current study, measuring approximately 27 km^2.

In 2013, one of us (NT) led a research expedition focused on recording commingled human remains in a burial cave on the island of Atiu. Rima Rau, or the “Cave of Five Hundred”, was used as a burial site probably during the prehistoric period. All human remains were returned to the cave immediately after macroscopic examination. No samples were collected for destructive analyses and therefore isotopic analyses could not be undertaken for palaeodietary reconstruction or radiocarbon dating. As a commingled assemblage with many bones broken post-mortem, a minimum number of individuals (MNI) was estimated at 42 individuals and 106 skeletal elements (i.e., maxillary or mandibular portions) were examined for this study.

Most of the remains inside the Rima Rau cave were available for surface collection and further excavation was therefore unwarranted. Only skeletal material from the main chamber was thoroughly mapped and collected and time constraints prevented the complete collection of skeletal material located in other areas of the cave. No postcranial material or isolated teeth were collected past ten meters from the cave entrance due to time constraints. No grave goods were collected although some *Tridacna* shells appear to have been placed on the chest of a few individuals.

Oral indicators of diet

Pathobiology and interpretation of oral conditions is reviewed extensively elsewhere (e.g., Hillson 2000; Lukacs 2012) and in the interests of space constraints, we are not doing so here. Assessments of sex-based differences in the frequencies of oral conditions are important for understanding culture-specific dietary practices (Milner 1991). Of special importance are differences in caries prevalence associated with sex. It has been observed in both archaeological and modern populations that females typically experience higher rates of carious lesions, periodontitis, and ante-mortem tooth loss (AMTL) (Demirci et al. 2010; Ferraro and Vieira 2010; Lukacs 2008; Lukacs 2011; Lukacs and Thompson 2006; Munblatt 1933; Willis and Oxenham 2013).

The reasons for sex-based differences are multifaceted and still not well understood. Salivary flow rate and composition, hormonal influences, and sex-linked heritability to carious susceptibility have been investigated as possible reasons for these observed differences between the sexes (Lukacs and Largaespada 2006; Patir et al. 2008; Vieira et al. 2008). Pregnancy appears to play a large role in female oral health, which would be expected if hormones affect oral health given the hormonal fluctuations associated with pregnancy. Food choices (aversions and cravings), salivary composition changes, and immune system compromises have all been associated with pregnancy and could negatively impact oral health (Gajendra and Kumar 2004; Lukacs and Largaespada 2006; Muramatsu and Takaesu 1994; Salvolini et al. 1998). Regardless, it is still understood that cultural factors that result in different food consumption patterns between men and women (Hunter and Linn 1979; Rozin et al. 1999) may influence susceptibility to certain oral conditions. In this study, while we will be considering other causes for susceptibility beyond diet, we will be examining the patterns of oral condition presentation between demographic groups (site, sex, age) to address dietary questions.

Isotopic analyses of diet

While the examination of oral conditions broadly estimates diet as an indirect consequence of food choices, isotopic analyses of cortical bone directly examines the proportions of types of foods eaten by an individual within the last few years of their lives. Stable isotope analysis is an increasingly utilized tool for understanding diet and several thorough reviews are available (Ambrose and Krigbaum 2003; Hedges et al. 2007; Katzenberg 2007; Schoeninger 2010), including a review of paleodietary reconstruction in the Pacific (Kinaston and Buckley 2013).

Carbon isotopic analysis ($\delta^{13}C$) can be used to differentiate between the consumption of marine and terrestrial plant foods, (Kinaston and Buckley 2013). Terrestrial C_3 plants display $\delta^{13}C$ values approximately between -33 to -23‰, while terrestrial C_4 plants display carbon values between -16 to -9‰ (Ambrose and Norr 1993; Chishom et al. 1982; Schoeninger and DeNiro 1984; Schoeninger and Moore 1992). While most marine plants follow the C_3 pathway, the difference between atmospheric and oceanic carbon reservoirs places marine plants between C_3 and C_4 terrestrial plants, around -12‰ (Sharp 2007). *Pandanus tectorius*, a commonly cultivated plant in Polynesia, follows another carbon fixating pathway (the CAM photosynthetic pathway) but will display carbon values indistinguishable from terrestrial C_3 plants (Boutton 1991; Sharp

2007). Generally, higher carbon values in Pacific studies can be associated with a larger marine component in their diet rather than increased ingestion of C_4 plants as there are a few C_4 plants of note in the Pacific, sea grapes (*Coccoloba uvifera*) and a few other seaweeds, and sugar cane (*Saccharum officinarum*). Neither are typically considered dietary staples in the prehistoric Pacific though some populations appear to have eaten large proportions of these plants (Marshall et al. 2008; Sharp 2007). There are small amounts of trophic level spacing for $\delta^{13}C$ values (+0 to +2‰ per trophic level), though this spacing is generally too small to observe except in controlled studies (Ambrose et al. 1997; Field et al. 2009).

Nitrogen isotope values ($\delta^{15}N$) mainly provide information about the trophic level of an individual's diet, with an animal displaying roughly 3-6‰ higher $\delta^{15}N$ values than their prey (Bocherens and Drucker 2003). Used in conjunction with carbon stable isotope ratios, $\delta^{15}N$ values can also be used to understand the proportions of terrestrial and marine foods in a diet as consuming foods from aquatic systems results in higher $\delta^{15}N$ values due to more trophic levels in aquatic food webs (Deniro and Epstein 1981; Schoeninger et al. 1983; Sealy et al. 1987).

Methods for recording oral health conditions

All observations of dental conditions were limited to presence/absence of the pathology to facilitate comparisons of multiple pathologies using the same statistical methodology. Teeth were removed from their alveoli when possible for closer examination. A hand magnifier (x 10) was used when necessary. Any occlusal edge chipping was recorded as present. For dental wear, dentin exposure (more than pinprick exposure) was considered present. For periodontitis, the Kerr method (1991; 1998) was used as per Hillson's recommendation (2001). In order to examine spatial differences in the dentition, all septa mesial to the 1st premolar (1st molar in deciduous dentitions) were considered anterior and all septa distal to that tooth type were considered posterior. Any evidence of periodontal changes rated "3" or greater using the Kerr method (where a breakdown of the contour was observable and associated with periodontitis) were recorded as present. Alveolar lesions are recorded if observed macroscopically. Differential diagnosis of alveolar lesions was not attempted. Ante-mortem tooth loss was differentiated from post-mortem tooth loss by evidence of remodeling of empty tooth sockets.

Carious lesions were considered present only if they were visibly cavitated. In archaeologically-derived skeletons, some teeth will have been lost ante-mortem as a result of progressive destruction from caries. Obviously, these teeth cannot be observed by investigators, and thus the caries prevalence determined when comparing the number of carious teeth to the total number of teeth creates a frequency smaller than the "true" prevalence. Some researchers have created equations to factor for the teeth lost to caries before death by including the number of teeth lost ante-mortem in a correcting equation (Lukacs 1995; Whittaker et al. 1981). As teeth are lost ante-mortem for a number of reasons and it is impossible to know how many were lost due to caries, many researchers are critical of these caries correction factors (Hillson 2001; Oxenham and Matsumura 2008; Wasterlain et al. 2009). No caries correction factors were included in this study.

All pathological recording was conducted by the first author (CS) to avoid inter-observer error. Individuals from the `Atele and Bourewa sites were recorded in the University of Otago Bioanthropology Laboratory. All Rima Rau individuals were recorded in an on-site laboratory before being repatriated to the burial cave.

Sex and age estimation of the ‘Atele collection was conducted by HRB. Differential preservation of postcranial material made age estimation using epiphyseal unions and pubic symphyseal degeneration difficult. Thus seriation by degree of dental attrition (Lovejoy 1985) was the primary method of assigning adults (18+ years) to age groups because of the differential preservation of postcranial material. Rather than assigning chronological age ranges, the relative age groups of young, middle, and old adults were presented. Sex estimation was carried out using the standards outlined in Buikstra and Ubelaker (1994).

Sex and age estimation of the individuals in the Bourewa and Rima Rau skeletal collections was conducted by CS. Sex and age estimations were conducted using the standards outlined in Buikstra and Ubelaker (1994). Establishing a paleodemographic census was not possible for commingled remains of the Rima Rau collection. As most bones were isolated, sex and age estimation for most of the individuals was not possible. Dental development was the only method feasible to estimate the age of individuals represented by either a single maxilla or mandible. Sex-based comparisons were not conducted on the Rima Rau skeletal sample. Determining the number of individuals present in the cave also had to be undertaken with caution because of the commingled nature of the remains. No mandibles or maxillae were assumed to belong to the same individual. This caveat is continued when presenting results in this study. Rather than displaying the prevalence rate of the oral pathologies by individual, they are presented by maxilla or mandible. Given the difficulties of age estimation for Rima Rau, the adults could not be categorized into more refined age groups like the ‘Atele and Bourewa individuals.

Methods used for isotopic analyses of diet

Carbon and nitrogen isotopic analyses of cortical bone collagen were conducted on adults from `Atele (*n* = 33) and Bourewa (*n* = 13). Individuals with cortical bone for isotopic analyses but no cranial material for the examination of oral conditions were not included in this study. Cortical bone fragments approximately 1200-1400 mg were isolated from each individual. Bones displaying pathological changes were excluded from sampling on the principle that changes in the metabolic pathways of the tissue as a result of disease may affect the isotopic values (Katzenberg and Lovell 1999; Olsen et al.) After sandblasting to remove surface impurities, collagen extraction and purification were carried out using a modified Longin method (Brown et al. 1988; Collins and Galley 1998; Longin 1971) by CS and RLK at the Department of Anatomy, University of Otago (Dunedin, New Zealand) and at the Max Planck Institute for Evolutionary Anthropology (Leipzig, Germany). The samples were demineralized in 0.5 M HCl at 4 ◦C and gelatinized in 3.00 pH HCl solution at 70 ◦C for 48 hours. After filtering (5-8 µm Elkay Ezee® mesh filter) and ultrafiltering (Amicon Ultra-0.5 Centrifugal Filter Units with Ultracel-30 membranes), the samples were frozen, then lyophilized for 48 hours.

Stable isotope analyses were conducted at the Department of Human Evolution, Max Planck Institute of Evolutionary Anthropology (Leipzig, Germany). Carbon and nitrogen stable isotope values were measured simultaneously using a Flash EA 2112 coupled to a DeltaXP continuous-flow isotope-ratio-monitoring mass spectrometer. Repeated measurements of working standards EVA-0009 (methionine), SRM 1577b (bovine liver), IAEA-N-1 and -N-2 (ammonium sulfate), IAEA-CH-6 (sucrose), and IAEA-CH-7 (polyethylene) were interspersed throughout the archaeological samples to correct the carbon and nitrogen isotope data. The analytical precision of the δ^{13}C and δ^{15}N measurements were less than 0.1‰ standard deviation.

Collagen integrity for carbon and nitrogen analyses was determined using %C by weight, %N by weight, and C/N ratios (Ambrose 1990; Ambrose and Norr 1992; DeNiro 1985). Collagen samples displaying C/N ratios between 2.9-3.6, %C values between 15-47%, and %N values between 5-17% were considered well preserved. All dietary stable isotope ratios were standardized to the international references standards for carbon and nitrogen (Vienna Pee Dee Belemnite [VPDB] and Atmospheric Nitrogen [AIR], respectively).

Analytical methods

Data were analyzed using Stata/IC 13.1 (StataCorp 2013). A subsample of nine individuals from the ‘Atele population (*n* = 221 teeth) was re-recorded for intra-observer error testing. Crude and category-specific prevalence of oral conditions were calculated from the raw data. Multi-level logistic regression was used to examine the relationship between various characteristics of the people under examination (for example, their location or sex) and oral conditions. The outcome variable for each of the models was whether or not each tooth/septa had the condition under examination (hence the need for a logistic model). Individual identifiers were included as random-effects in the regression models to account for the fact that the pathologies from one individual are likely to be correlated. One of the advantages of using this method is that it allows for individuals having a varying number of observable teeth. It also means that multiple explanatory variables can be considered simultaneously providing adjusted estimates, which are often preferable to unadjusted estimates (which is all that is available when using methods such as chi-square for contingency tables where only two variables can be considered at a time).

Three classes of logistic models were fitted. From these models, estimates of the odds ratios (OR) were produced. These ratios describe the association between a particular predictor and the outcome in question. In all cases, there were individual models fitted for each of the pathologies.

In the first class of models, the predictors were burial site (Rima Rau, Bourewa, and ‘Atele), dental arch (anterior/posterior), jaw (maxillary/mandibular), and age (subadult/adult). Age is included in the model to account for the different proportions of age categories in the burial sites which are critical when making comparisons. In these models, because the burial site variable had three categories, Rima Rau became the reference category and the other two sites were compared to that site through the odds ratios. We then conducted a linear combination of estimators to compare ‘Atele and Bourewa.

In the other two classes of models, no subadults were included. Instead, sex, position in the jaw, dental arch, and adult age categories (young, middle, and old adults) were included. For the adult age categories, young adults were the reference category in the model, and then a linear combination of estimators were conducted between middle and old adults. As the Rima Rau assemblage has no adult age or sex data, the assemblage is not included in this model. The second class of model included both assemblages to compare `Atele and Bourewa with the adult age and sex predictors included. In the third and final model, each site was tested separately to understand site-specific age and sex differences. Burial mound was included as a predictor variable when examining the `Atele mounds.

Interpreting oral indicators of diet and isotopic analyses is difficult due to the contrasting nature of the two data types. Although individual frequencies of oral conditions are possible, investigations of oral indicators of diet tend to focus on tooth frequencies due to their large sample size and robust statistical power. The data is largely categorical or ordinal. Isotopic analyses, conversely, yield continuous data from a bone or tooth sample that represents an individual. Factoring in sampling issues wherein an individual from an archaeological excavation might have bones suitable for isotopic analyses but no teeth due to differential preservation or vice versa and the marriage of these two disparate data sets beyond qualitative review becomes even more difficult.

In order to compare isotopic values to oral condition frequencies, we follow similar comparative methods as Turner (2013). For isotopic analyses, t-tests were conducted to compare the carbon and nitrogen isotopic values between sites and sexes. Individual frequencies of conditions were calculated for Bourewa and `Atele individuals by calculating the total observed number of a given oral condition and dividing by the total number of teeth/alveoli observed (e.g., number of carious teeth observed/total number teeth in an individual). Pearson's correlation coefficients were measured between condition frequencies and carbon and nitrogen isotopic values.

Oral health **indicators of diet in the samples**

All observations were in acceptable concordance following commonly accepted criteria for intra-observer agreement (Landis and Koch 1977). Table 2 summarizes the demographic structure of the two sites with age and sex information. Tables 3 through 6 show the raw prevalence of all pathologies, both by site and for the sites combined. For all pathologies other than periapical cavities, Tables 7 through 10 show the results using multi-level logistic regression.

There were too few instances of periapical cavities to conduct any statistical analyses, so they were examined qualitatively. There appear to be no sex-based differences in periapical cavities and no subadults displayed evidence of this pathology. Although the overall prevalence of periapical cavites was low in all samples, the Rima Rau sample displayed roughly double the prevalence compared with the other two samples (1.9% compared to 0.9% and 0.7%). No periapical cavities were present in To-At-1 individuals from Atele, but the To-At-2 sample displayed a prevalence rate of 1.2%.

There were significantly reduced odds of all pathologies for subadults compared with adults in the first class of models (Table 7). In the instance of AMTL, age was omitted from the model by the statistical program because age predicted presence or absence perfectly. Age was included in the model to remove the effect of age when looking at the associations for the other characteristics. For example, the increased odds for caries of 2.06 for posterior teeth compared to anterior are adjusted for the effect of age. If age was not included we would not know if that effect was due to the tooth position or due to age as we already know that increasing age has an impact on oral health (Demirci et al. 2010). The significant effect of age serves as evidence that age needed to be included in the model. In this model, the odds of Bourewa individuals displaying pathologies were significantly different from both Rima Rau and ‘Atele, with higher odds of AMTL and wear. There were no significant effects for the comparison of Rima Rau and ‘Atele samples. Teeth and alveoli in the posterior dental arch displayed significantly more AMTL, carious lesions, and periodontal disease but less dentin exposure than anterior teeth/alveoli. Maxillae experienced significantly less chipping and periodontal disease.

When examining the second regression model (Table 8), which does not include the Rima Rau assemblage and takes adult age into consideration, there were no longer significantly different odds of oral conditions between `Atele and Bourewa. Adult age categories significantly affect the odds of displaying AMTL, caries, and periodontitis for both sites. There are still no significant differences between the sexes. The odds between anterior and posterior teeth remain unchanged for all oral conditions despite the removal of the Rima Rau assemblage and inclusion of adult age as a predictor. Compared to the first model, there were no longer significant differences between maxillae and mandibles regarding AMTL. The odds for mandibular alveoli to display periodontal disease were still significantly less than maxillary alveoli.

In the model with only Bourewa (Table 9), adult age categories predicted AMTL and caries perfectly and could not be included in the model. The number of observable alveoli in the Bourewa assemblage (*n* = 101) was too small for multi-level logistic regression of periodontitis. The sample sizes were especially small when trying to compare adult age categories, where only two alveoli from old adults were observable. A chi-squared test between the sexes does show significant differences, $\chi^2(1, n = 101) = 6.74$, p=0.009. Other than periodontitis, only the odds of chipping are significantly different with males displaying higher odds of chipped occlusal surfaces.

In the `Atele only model (Table 10), burial mound To-At-2 displays significantly higher odds of chipped occlusal surfaces. There are significant differences between the adult age categories regarding AMTL, carious lesions, chipping, and periodontitis. There are no significant differences between the sexes.

Paleodietary findings in the samples using stable isotope analyses

Regarding isotopic analyses of Bourewa and ‘Atele, all samples were within acceptable parameters of collagen integrity (C/N ratio, %C, %N). Figure 2 displays δ^{13}C and δ^{15}N bone collagen results by sex and burial site. Descriptive statistics for the isotopic values are displayed on Table 11. Regarding carbon, there was a significant effect for burial site, $t(44) = 11.00$, $p < .001$ with Bourewa displaying higher $\delta^{13}C$ values. There was also a significant effect for burial site regarding nitrogen isotopic values, $t(44) = -2.43$, $p = 0.019$ with the `Atele individuals displaying higher $\delta^{15}N$ values. Within the `Atele assemblage, females displayed significantly lower carbon values, $t(29) = -2.63$, $p = 0.01$, but there were no significant effects regarding nitrogen isotopic values, $t(29) = -1.98$, $p = 0.058$. In the Bourewa assemblage there were no significant effects regarding sex for carbon, $t(6) = -1.37$, $p = 0.221$, or nitrogen, $t(6) = -0.51$, $p = 0.632$.

Table 12 displays the results of the Pearson correlations. Figures 3 through 7 display the carbon and nitrogen isotopic values with the percentage prevalence of oral conditions. In the Bourewa assemblage, there is a significant positive correlation between $\delta^{13}C$ values and caries, $r(11) = 0.56$, $p = 0.045$, $\delta^{15}N$ values and AMTL, $r(14) = 0.53$, $p = 0.038$, and $\delta^{13}C$ values and periodontitis, $r(11) = 0.77$, $p = 0.010$. Though there were no significant correlations in the `Atele assemblage between isotopic values and pathologies, there was a strong positive correlation between AMTL and $\delta^{15}N$, $r(31) = 0.34$, $p = 0.053$.

DISCUSSION

The anatomical trends within the jaw mostly conform to the morphological variance expected within teeth. The increased morphological complexity of the posterior teeth tend to leave these teeth more susceptible to carious lesions (Juhl 1983; König 1963). The increased odds of AMTL and periodontal disease in the posterior portion of the dental arch were possibly a result of the complex interactions of carious lesions, periodontal disease, and subsequent tooth loss. The decreased odds of chipping in maxillary teeth is also expected, as they are more fracture-resistant than mandibular teeth (Schatz et al. 2001). The greater odds of periodontal disease in mandibular teeth, however, are more difficult to explain. There are currently no physiological explanations in the clinical literature explaining this pattern.

The low prevalence of periapical cavities throughout all samples is possibly associated with the low rate of occlusal wear (Dias and Tayles 1997). Though cavities can form as a result of carious infections traveling through the tooth root and causing acute periapical abscessing heavy attrition can also expose the tooth pulp to secondary infection, as observed in prehistoric Maori populations (Kieser et al. 2001; Taylor 1963).

Differences in diet between the three sites

Examining the first regression model (Table 7), no significant differences in any of the pathologies were observed between Rima Rau and ‘Atele samples despite their physical distance. The diet of the Bourewa individuals was significantly different from the diets of the other two samples when examining the regression model that does not account for adult age. However, when adult age categories were included in the second model, there were no significant differences between Bourewa and `Atele. Although there were no significant differences between the sites regarding adult age categories using a simple chi-squared, the demographic differences were enough to drastically change the comparative results. This raises questions about the validity of comparing a commingled assemblage such as Rima Rau, or any assemblage where adult age information is not available.

Inter-mound differences in the frequencies of the observed pathologies at ‘Atele were few. Although To-At-2 individuals displayed increased odds of carious lesions, it was not to a significant degree. The significantly reduced wear in To-At-2 individuals is in corroboration with the isotopic evidence as soft, roasted root vegetables would cause less attrition than gritty shellfish and other marine resources.

The lack of differences in oral health between the ‘Atele and Bourewa samples are in direct contrast with the isotopic evidence of diet. Inter-site isotopic comparisons found significant differences between Bourewan and ‘Atele individuals. The increased wear in the Bourewa sample compared with the other two samples is consistent with the patterns previous researchers have observed in populations consuming a diet rich in marine foods (Littleton and Frohlich 1993). The increased odds of AMTL is more difficult to explain, since AMTL can be associated directly or indirectly with all of the other pathologies studied in this chapter, as well as a wide range of other etiologies such as trauma, and tooth ablation (Hillson 1996). Ultimately, the apparently higher rate of AMTL observed in the Bourewa sample may be a sampling issue.

The isotopic evidence (significantly higher δ^{13}C values in the Bourewa assemblage) supports that they had a much larger marine component in their diet compared to the ‘Atele individuals. Most Fijians and Tongans traditionally relied heavily on marine resources whether they lived at the coast or inland (Field et al. 2009; Jones 2009). The isotopic differences between the Bourewa and ‘Atele individuals may be explained by the proximity of an unusually broad fringing-reef flat, still renowned for its productivity, to the Bourewa site (Nunn 2009; Robb and Nunn 2014), which might be expected to contribute a greater proportion of marine foods to Bourewan diets than elsewhere.

Additionally, Atiu and Tongatapu are both relatively small islands that predicated the need to utilize all available resources for food. For the most part, these island populations were unified social groups or at least unified enough to exert some measure of control over surrounding islands (Clark et al. 2008; Crocombe 1967). In contrast, the prehistoric inhabitants of Viti Levu had varied economic and subsistence specializations with distinct territorial boundaries that may have made utilizing the diverse biomes of Viti Levu difficult(Clark and Anderson 2009; Field 2004). As such, coastal inhabitants of Viti Levu may have relied more heavily on marine resources than the inhabitants of the smaller islands, and the burial location of Bourewa suggests these Fijians lived near the coast.

The relationships between oral indicators of diet and paleodietary isotope values

Regarding the relationships between isotopic values and oral condition frequencies in individuals, the only significant relationships were in the Bourewa assemblage. A closer examination of the graphs for caries and periodontitis reveal an outlier with high carbon and nitrogen values and a higher frequency of caries and periodontitis compared to the rest of the assemblage. Removal of this individual reduces the correlations between the isotopic values and caries and isotopic values and periodontitis to a non-significant relationship.

Ante-mortem tooth loss and δ^{15}N values provide the only strong relationship between both sites, though we recognize the correlation in the ‘Atele assemblage is non-significant ($p = 0.053$). It is interesting that diet-related causes of AMTL (caries, periodontitis, and wear) are not related to δ^{15}N values. One possibility is that the relationship between AMTL and δ^{15}N values is not interconnected with caries, periodontitis, and wear, but with trauma. Increased δ^{15}N value in these two assemblages is largely associated with the consumption of more marine foods. The consumption of fish and shellfish, compared to root vegetables cooked until soft, may have resulted in increased dental trauma. If this were the case, however, we would have also expected a relationship between δ^{15}N values and occlusal edge chipping. Trauma from interpersonal violence (IPV) in the form of ritualized sporting was observed in the `Atele assemblage (Scott and Buckley 2014). Though dental trauma can arise from IPV, dental trauma occurs very rarely in modern IPV incidents (Ferreira et al. 2014), and when dental trauma does occur due to IPV it tends to manifest as chipping at the cemento-enamel junction, not the occlusal edge (Lukacs 2007).

As isotopic analyses are a means of directly addressing diet, why are there so few relationships between oral conditions and the isotopic results? Differences in diet may not fully explain the prevalence of these conditions. Extramasticatory use can cause dental wear, chipping, alveolar lesions and tooth loss (Molnar 2011). In addition, while dental diseases are often linked as a risk factor for other diseases (DeStefano et al. 1993; Joshipura et al. 1996), they can also be affected by various diseases and conditions (Lalla et al. 2007; Lamster et al. 2008; Petersen 2003; Ritter 2006; Sandberg et al. 2000). It is also a possibility that the aspects of diet revealed by isotopic analyses (e.g., proportions of marine vs. terrestrial foods and relative amount of animal protein consumed) are not the dietary characteristics meaningfully affecting oral conditions. Other aspects, such as micronutrient content, texture, and timing intervals of meals can all affect the rate of oral conditions (Dreizen 1970; Geddes 1994; Nakahara et al. 2013), but cannot be directly examined using paleodietary isotopic analyses.

Sex-based differences in diet

The lack of effect of sex on oral health is also in conflict with the isotopic findings from ‘Atele. While isotopic analyses of the Bourewa individuals found no sex-based differences in diet, there were significant differences in the ‘Atele sample with females displaying significantly lower $\delta^{13}C$ and $\delta^{15}N$ values than males. The lower values suggest an increased proportion of terrestrial C_3 foods and fewer marine/lagoon resources in female diet.

Examination of the prevalence rates on Table 3 show there are large differences in dental wear between the sexes at ‘Atele, even if they are not statistically significant. A decreased prevalence of wear in males is in conflict with the isotopic results, as an increased reliance on fish and shellfish (as indicated in the isotopic evidence) would ostensibly increase occlusal wear compared with a softer, plant-based diet (Molnar 1971; Walker 1978).

The dietary differences between the sexes at ‘Atele, while significant from the isotopic analyses, may be too small to have affected oral health. Although many carbohydrate-rich crops relied on in agricultural and horticultural societies are cariogenic (e.g., corn and wheat), the root crops that form the staples of Pacific diet may be only slightly cariogenic, if not cariostatic. Heat-treated and finely ground starches, such as roasted and mashed root vegetables, are more cariogenic than raw starches but still less cariogenic than sugars (Rugg-Gunn and Nunn 1999). Cooked starches have been found to be one-half to one-third as cariogenic as simple sugars (Bowen et al. 1980; Koulourides et al. 1976), and trace vitamins and minerals such as vitamins A, C, and D and fluoride can contribute to cariostatic/cariopreventative effects in foods (Dreizen 1970). Although low in vitamin D, many of the staple plants in the Pacific (taro, yams, sweet potato, bananas) contain vitamins A and C and taro and yams are also relatively high in fluoride (Barnaud 1975; Murray 1986). Environmental fluoride levels are difficult to ascertain. While volcanic activity contributes to heightened environmental fluoride levels calcium in limestone such as the coralline limestone that constitutes many raised coral reef islands (D'Alessandro 2006), can bind to fluorine and defluoridate water, negating any carioprotective advantage (Reardon and Wang 2000). To our knowledge, no fluoride studies have been conducted for any of the islands studied so we cannot comment on whether this could influence the caries profile of these assemblages, and it seems unlikely that fluoridation would explain the sex-based differences as both sexes would likely be drinking from the same water sources.

While few studies have conducted an in-depth comparison of oral health between the sexes in prehistoric Pacific islanders none have found differences in caries rates. The Latte-Period site of Apurgan (1000 - 1521 CE) in the Marianas Islands was examined by Douglas et al. (1997). Regarding oral health, Douglas et al. (1997) found that females displayed significantly more periapical cavities, alveolar resorption, and attrition, but no differences in AMTL or caries compared with males. They did not propose any culture-specific reasons behind these patterns, only that differential susceptibility, resource access, or culturally-mediated behaviors may be factors. A study focusing on carious lesions in the permanent dentition of prehistoric Easter Islanders found that males displayed a higher caries prevalence rate than females (30.1% vs. 22.6%, respectively), though the difference was not statistically significant (Owsley and Miles 1985). An unpublished Master's thesis focusing on dental health in the Pacific (from multiple prehistoric assemblages, including the `Atele assemblage) examined sex-based differences in dental wear, but did not compare the sexes for any dental diseases (Evans 1987).

In a skeletal sample from Taumako (c. 1,200 – 1,650 CE), Kinaston (2010) found no sex-based differences in the severity of wear, or prevalence of caries, calculus, cavities, periodontal disease, and AMTL. Yet she did observe significant sex-based differences in the frequencies of oral pathologies in the Teouma skeletal sample from one of the oldest cemetery sites in Remote Oceania (c. 1,050 BCE): Teouma males displayed significantly higher rates of calculus and AMTL compared with the females. In addition, when examining the Nebira site from Papua New Guinea (c. 1,150 – 1,650 CE), Kinaston observed that males had significantly higher rates of wear compared with females. None of the sites examined by Kinaston displayed sex-based differences in caries rates.

Modern epidemiological studies could provide information of whether modern Pacific Islanders have similar sex-based patterns of risk to caries development. While modern epidemiological studies have been conducted on Pacific Islanders (Doherty et al. 2010; Parker et al. 2010), they have focused more on childhood risk and 'race-based' disparities regarding access to health care; sex differences are yet to be explored using these databases.

From 20th century medical studies of oral health in living populations the changes in dental disease prevalence with the advent of European dietary influences can be seen. Faine and Hercus (1951) observed high rates of caries (35.4%, 3528/9965 teeth) and periodontal disease (26.8%, 92/343 individuals) on Rarotonga, the main point of European contact in the Cook Islands, but did not consider sex-based differenced. The island of Pukapuka is more isolated than Rarotonga, particularly when Davies (1952; 1956) visited to collect data on oral health, 45% of individuals were affected by periodontal disease (225/497 individuals), a higher rate compared with those on Rarotonga. In contrast, the caries prevalence on Pukapuka was markedly lower compared than Rarotonga (12.1%, 1573/12981 teeth). It should also be noted that these high rates of periodontal disease and caries on Pukapuka are similar to the average found between the three prehistoric samples reported here (50.3% of individuals and 11.8% of teeth, respectively). Davies found significantly more caries in females, significantly higher rates of attrition in males, and no differences in the frequency of periodontal disease between the sexes in the Pukapuka Island population (Davies 1952; Davies 1956). In the Pukapuka population there was no association between caries and hypoplasia or caries and dental wear (Davies 1952; Davies 1956).

A study of three Papua New Guinean villages relatively isolated from Western influence (Sinclair et al. 1950) found that villagers were less affected by caries (4.7%; 419/8988 teeth affected by caries) than the Cook Islanders studied by Faine and Hercus (1951) and Davies (1952; 1956). Sex differences in caries rates were not reported in the study. Although only descriptive frequencies were listed in the original research, a Pearson's chi-squared shows males were significantly more affected by periodontal disease.

Comparing the assemblages in this study with those from past research, it becomes clear that there is no unifying pattern of oral conditions within the Pacific across temporal or spatial distances. European dietary influences may affect many of the modern populations, but the prehistoric assemblages also display a wide variety of prevalence rates. For example, caries rate prevalence by tooth range between 9.8% in prehistoric Hawai`i (Keene 1986) to 31% in Lapita-era Vanuatu (Kinaston 2010). The caries rates reported here for all three sites are high relative to global prehistoric populations. With a mean per-tooth rate of 11.8%, the Pacific populations experienced carious lesions at a prevalence comparable to many Pre-Industrial mono-crop agricultural societies (Larsen 1995; Turner 1979).

Within all of these dental studies in the tropical Pacific, including this study, only the modern studies by Davies (1952; 1956) found higher rates of carious lesions in females compared to males. The lack of sex-based differences in caries prevalence is in conflict with the global phenomenon of females experiencing significantly more caries than males (Lukacs and Largaespada 2006), and there are no obvious reasons why tropical Pacific populations were/are generally unaffected by the hormonal and genetic causes for increased caries susceptibility in females. Dietary differences seem an unlikely cause, given that the isotopic evidence suggests that females, consuming proportionately more starchy root vegetables and fewer marine animals than males, were eating an ostensibly more cariogenic diet. Genetic or environmental factors specific to the inhabitants of the Pacific Islands may nullify or counterbalance the worldwide phenomenon, but will be difficult to ascertain.

Given that high fertility rates are associated with high rates of caries, AMTL, and periodontitis in females (Lukacs 2008; Willis and Oxenham 2013), is it possible that low rates of fertility could be associated with relatively low rates of oral conditions? The idea is intriguing, but even nonparous post-adolescence females display higher rates of oral disease (Lukacs and Largaespada 2006; Stoughton and Meaker 1932). The `Atele assemblage contained a high proportion of infant burials compared to other prehistoric assemblages (Buckley 2001), which may be indicative of high fertility in the living population (McCaa 2002). The Bourewa assemblage only contained one non-adult (estimated around 13 years of age) and the Rima Rau assemblage had 11/260 jaw fragments containing deciduous teeth or erupting permanent teeth. Thus, very few non-adults were present in these two assemblages. Unfortunately, paleodemographic estimations require larger sample sizes than these assemblages can offer. Without fertility estimations in prehistoric Fiji or Tonga, this avenue cannot be explored completely to satisfaction, but it is hoped that future paleodemographic research could investigate the potential relationships between fertility and oral conditions in the Pacific.

Instead, perhaps the focus should be turned to the other sex: are males in prehistoric tropical Oceania experiencing some environmental factor, cultural influence, and/or genetic traits that is leaving them as susceptible to caries and other oral conditions as females? A study found that caries rates in modern Maori males and females are similar (79.8% and 80.4% of individuals, respectively) (Inoue 1993). As a population of similar ancestry as Fijians and Tongans (Kayser et al. 2006) living in a temperate climate, environmental factors are less likely an underlying cause and shared cultural traits (whether dietary or otherwise) and/or genetic traits should be considered.

CONCLUDING REMARKS

We examined three prehistoric Pacific sites and compared the presence of dental wear and the prevalence rates of oral pathology. We did not find significant differences between any of the three sites when adult age is taken into account, in accordance with our initial hypothesis. The site-based differences are inconsistent with isotopic analyses of diet, which found differences in between the Bourewa and `Atele assemblages.

Comparing oral indicators of diet with isotopic values, there was only a significant relationship between AMTL and $\delta^{15}N$ once an outlier was addressed. We acknowledge the difficulty of comparing two disparate data sets, but as the isotopic values are direct indicators of individual diet, oral conditions prevalence within Bourewa and `Atele were influenced by factors other than diet or dietary attributes that cannot be quantified by isotopic analyses. Our second hypothesis is rejected.

One of the more significant findings to emerge from this study was the lack of sex-based differences in oral conditions, despite differences in diet as observed from stable isotope analyses. Our hypothesis that were would be sex-based differences in diet as evidenced by oral conditions is therefore rejected. We posit that this discrepancy is because the differences in diet did not significantly affect oral conditions in females. Past research on oral conditions in Pacific populations, both prehistoric and modern, also reveals few differences between the sexes, suggesting a geographically-specific phenomenon affecting oral condition prevalence (especially caries) in females. Instead, some environmental or genetic factor(s) affecting Oceanic populations may be affecting oral health in females. Conversely, genetic or cultural factors leaving males more susceptible to oral conditions may be the cause of the similar prevalence rates.

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Tables

Table 1. Site and sample summary.

	‘Atele	Bourewa	Rima Rau
Date	490 - 220 calBP ±22	750 - 0 calBP	Pre/proto-historic
Location	Tongatapu, Tonga	Viti Levu, Fiji	Atiu, Cook Islands
Nature of burials	Two burial mounds	Burials cutting into older settlement layers	Burial Cave
Number of individuals examined	89	24	MNI =42
Number of teeth	1244	303	835
Number of interalveolar septa	941	172	650

Table 2. Age and sex distribution of the two sites with non-commingled remains.

	Subadults	Females	Males	Young	Middle	Old	Adults total	Total
‘Atele	28	23	12	16	11	7	61	89
To-At-1	18	10	5	8	5	0	20	38
To-At-2	10	13	7	8	6	7	23	33
Bourewa	1	9	4	2	2	5	22	24

Table 3. Raw pathology prevalences of the ‘Atele population. [1]Periodontitis is presented per septa, not per tooth.

Adults			Burial Mounds				Total	
Females	Males		To-At-1		To-At-2			
Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)
63/393 (16.0)	6/6 (100)	23/212 (10.9)	10/38 (26.3)	35/419 (8.4)	15/31 (48.4)	66/543 (12.2)	33/84 (39.3)	118/1105 (10.7)
88/363 (24.2)	9/11 (81.8)	37/203 (18.2)	22/35 (62.9)	48/381 (12.6)	23/31 (74.2)	108/523 (20.7)	51/79 (64.6)	181/1046 (17.3)
50/528 (9.5)	4/12 (33.3)	33/297 (11.1)	7/38 (18.4)	24/662 (3.6)	9/33 (27.3)	62/733 (8.5)	21/89 (23.6)	101/1615 (6.3)
29/122 (23.8)	9/11 (81.8)	88/245 (35.9)	18/24 (75)	71/204 (34.8)	17/27 (63)	70/289 (24.2)	45/66 (68.2)	54/243 (22.2)
52/364 (14.3)	8/11 (72.7)	38/228 (16.7)	10/22 (45.5)	39/342 (11.4)	18/25 (72)	65/450 (14.4)	36/61 (59)	129/941 (13.7)
3/427 (0.7)	2/12 (16.7)	2/243 (0.8)	0/34 (0)	0/526 (0)	5/27 (15.6)	7/596 (1.2)	7/79 (8.9)	9/1274 (0.7)

Subadults									
	Young		Middle		Old		All Adults		
Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)	Per Individual A/O (%)
7/286 (2.5)	6/14 (42.9)	11/304 (3.6)	6/9 (66.7)	49/165 (29.7)	4/5 (80)	24/85 (28.2)	30/58 (51.7)	111/819 (13.6)	12/23 (52.2)
22/267 (8.2)	14/14 (100)	74/288 (25.7)	6/8 (75)	17/159 (10.7)	3/4 (75)	25/79 (31.7)	41/57 (71.9)	159/779 (20.4)	19/23 (82.6)
0/477 (0)	3/14 (21.4)	3/372 (0.8)	4/9 (44.4)	21/222 (9.5)	6/6 (100)	56/160 (35)	21/61 (34.4)	101/1138 (8.9)	11/23 (47.8)
5/81 (6.2)	12/14 (85.7)	66/185 (35.7)	6/9 (66.7)	22/100 (22)	5/5 (100)	32/50 (64)	43/57 (75.4)	156/519 (30.1)	17/23 (73.9)
4/125 (3.2)	7/14 (50)	31/276 (11.2)	7/9 (77.8)	27/182 (14.8)	5/5 (100)	25/87 (28.7)	34/54 (63)	125/816 (15.3)	14/22 (63.6)
0/334 (0)	0/14 (0)	0/303 (0)	2/9 (22.2)	2/205 (1)	3/6 (50)	5/146 (3.4)	7/54 (13)	9/949 (1)	3/22 (13.6)

	Per Individual A/O (%)
Caries	3/26 (11.5)
Chipping	11/24 (45.8)
AMTL	0/28 (0)
Dental Wear	2/9 (22.2)
Periodontitis[1]	2/7 (28.6)
Periapical Cavities	0/25 (0)

Table 4. Raw pathology prevalences of the Bourewa population. [1]Periodontitis is presented per septa, not per tooth.

Adults					Total	
Middle	Old		All Adults			
Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)
2/51 (3.8)	2/3 (66.7)	2/18 (11)	13/18 (17.2)	37/229 (16.2)	13/19 (68.4)	37/248 (14.9)
10/43 (23.2)	1/3 (33)	3/16 (18.8)	10/17 (58.8)	29/204 (14.2)	10/18 (55.6)	29/223 (13.0)
8/62 (12.9)	4/5 (80)	44/69 (63.8)	12/22 (54.6)	84/364 (23.1)	13/24 (54.2)	88/391 (22.5)
23/30 (76.7)	2/2 (100)	10/13 (76.9)	18/18 (100)	79/140 (56.4)	18/19 (94.7)	79/152 (52)
2/43 (4.7)	1/1 (100)	2/2 (100)	9/15 (60)	22/155 (14.2)	9/16 (56.3)	22/172 (12.8)
0/61 (0)	1/5 (20)	1/52 (1.9)	3/22 (13.6)	3/302 (1)	3/24 (12.5)	3/332 (0.9)

Subadults							
	Females		Males		Young		
Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)	Per Individual A/O (%)	Per Tooth A/O (%)	Per Individual A/O (%)
0/19 (0)	4/7 (57.1)	6/85 (7.1)	3/3 (100)	15/65 (23.1)	2/2 (100)	5/55 (9)	1/2 (50)
0/19 (0)	4/7 (57.1)	11/78 (14.1)	2/3 (66.7)	10/51 (19.6)	1/2 (50)	3/55 (5.5)	2/2 (100)
0/23 (0)	6/9 (66.7)	34/140 (24.3)	3/4 (75)	25/93 (26.9)	0/2 (0)	0/59 (0)	2/2 (100)
0/12 (0)	7/7 (100)	36/52 (69.2)	3/3 (100)	18/37 (48.7)	2/2 (100)	4/29 (13.8)	2/2 (100)
0/17 (0)	2/5 (40)	3/49 (6.1)	3/3 (100)	13/52 (25)	1/2 (50)	5/47 (10.6)	1/2 (50)
0/26 (0)	1/9 (11.1)	1/110 (0.9)	1/4 (25)	1/106 (0.9)	0/2 (0)	0/55 (0)	0/2 (0)

	Per Individual A/O (%)
Caries	0/1 (0)
Chipping	0/1 (0)
AMTL	0/1 (0)
Dental Wear	0/1 (0)
Periodontitis[1]	0/1 (0)
Periapical Cavities	0/1 (0)

Table 5. Raw pathology prevalences of the Rima Rau population. Prevalence rates per bony element are reported rather than per individual. [1]Periodontitis is presented per septa, not per tooth.

	Subadults		Adults			Total
	Per Element A/O (%)	Per Tooth A/O (%)	Per Element A/O (%)	Per Tooth A/O (%)	Per Element A/O (%)	Per Tooth A/O (%)
Caries	0/8 (0)	0/52 (0)	7/19 (36.8)	9/107 (8.4)	29/85 (34.1)	44/341 (12.9)
Chipping	2/8 (25)	3/52 (5.8)	10/19 (52.6)	26/106 (24.5)	35/83 (42.2)	71/335 (21.2)
AMTL	0/11 (0)	0/111(0)	8/23 (34.8)	28/308 (9.1	26/105 (24.8)	71/906 (7.8)
Dental Wear	0/6 (0)	0/24 (0)	11/19 (57.9)	25/71 (35.2)	31/81 (38.3)	161/600 (26.8)
Periodontitis[1]	0/5 (0)	0/42 (0)	12/23 (52.2)	48/267 (18.0)	29/70 (41.4)	102/650 (15.7)
Periapical Cavities	0/11 (0)	0/105 (0)	4/23 (17.4)	5/295 (1.7)	12/80 (15.0)	15/803 (1.9)

Table 6. Raw pathology prevalences of all sites, combined. [1]Periodontitis is presented per septa, not per tooth.

	Per Tooth A/O (%)	Per Element/Individual A/O (%)
Caries	199/1694 (11.8)	75/188 (39.9)
Chipping	28/1604 (17.5)	97/182 (53.3)
AMTL	260/2912 (8.9)	60/218 (27.5)
Dental Wear	294/995 (29.6)	94/166 (56.6)
Periodontitis[1]	253/1763 (14.4)	74/147 (50.3)
Periapical Cavities	27/2418 (1.1)	22/183 (12.0)

Table 7. Model 1 of multi-level logistic regression. The models in this table incorporate all the available data. * marks statistical significance ($p < 0.05$). The effect of age from the model for AMTL could not be estimated because it predicted AMTL perfectly.

Model Class 1	AMTL	Caries	Chipping	Periodontitis	Wear
Burial Site					
Rima Rau	1	1	1	1	1
Bourewa	8.23*	3.53	0.48	1.46	5.30*
Atele	0.97	2.04	0.73	1.35	0.94
Bourewa-`Atele	8.53*	1.73	0.65	1.11	5.57*
Age					
Adult		1	1	1	1
Subadult		0.46*	0.26*	0.064*	0.25*
Dental Arch					
Anterior	1	1	1	1	1
Posterior	2.45*	2.06*	0.89	2.42*	0.3*
Jaw					
Maxillary	1	1	1	1	1
Mandibular	2.82*	0.81	0.70	0.42*	1.26

Table 8. Model 2 of multi-level logistic regression. In this regression, only Bourewa and `Atele are included in the model. C, N, burial site, adult age categories, sex, dental arch, and jaw are included in Model 2.

Model Class 2	AMTL	Caries	Chipping	Periodontitis	Wear
Burial Site					
Bourewa	1	1	1	1	1
`Atele	0.48	3.82	0.83	0.74	0.20
Adult Age					
Young	1	1	1	1	1
Middle	16.48*	14.00*	0.44	1.27	0.96
Old	438.21*	37.40*	1.22	10.21*	2.95
Old-Middle	26.57*	2.67	2.79	8.06*	3.07
Sex					
Female	1	1	1	1	1
Male	1.58	1.18	1.13	2.46	0.46
Dental Arch					
Anterior	1	1	1	1	1
Posterior	2.58*	2.43*	0.66	2.07*	0.12*
Jaw					
Maxillary	1	1	1	1	1
Mandibular	1.58	0.75	0.67	0.42*	0.79

Table 9. Model 3a of multi-level logistic regression. Only Bourewa is included in this model. The effect of age from the model for AMTL and caries could not be estimated because age predicted these conditions perfectly. Sample size was too small for multi-level logistic regression of periodontitis.

Model Class 3a	AMTL	Caries	Chipping	Periodontitis	Wear
Adult Age					
Young			1		1
Middle			0.11*		24.00*
Old			30.33*		25.45*
Middle-Old			2.71		1.06
Sex					
Female	1	1	1		1
Male	2.32	5.5	10.50*		2.73

Table 10. Model 3b of multi-level logistic regression. Only `Atele is included in this model, and burial mounds are compared for oral conditions

Model Class 3b	AMTL	Caries	Chipping	Periodontitis	Wear
Burial Mound					
To-At-1	1	1	1	1	1
To-At-2	0.30	0.29	2.28*	0.77	0.35
Adult Age					
Young	1	1	1	1	1
Middle	16.23	33.77*	0.29*	1.70	0.68
Old	427.05*	84.61*	0.92	7.02	6.17*
Middle-Old	26.31*	2.51	3.15*	4.13	9.14*
Sex					
Female	1	1	1	1	1
Male	0.74	0.49	1.06	2.08	0.59

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Table 11. Descriptive summary of δ^{13}C and δ^{15}N results by site and sex.

Site	δ^{13}C		δ^{15}N		*n*
	Mean	σ	Mean	σ	
Bourewa	-15	0.5	8.7	0.5	13
Females	-14.7	0.9	8.6	0.3	5
Males	-15.3	0.4	8.8	0.9	3
`Atele	-17.6	0.8	9.2	0.6	33
Females	-17.8	0.5	9	0.5	19
Males	-17.1	1	9.5	0.7	12

Table 12. Results of Pearson's correlations coefficients. * marks significance.

Bourewa	Caries		AMTL		Periodontitis		Wear		Chipping	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
$\delta^{13}C$	0.56	0.045*	0.32	0.231	0.77	0.010*	0.04	0.896	-0.47	0.105
$\delta^{15}N$	0.51	0.074	0.53	0.038*	0.61	0.056	0.12	0.692	-0.44	0.134
`Atele										
$\delta^{13}C$	-0.17	0.338	-0.08	0.656	-0.02	0.920	0.03	0.861	0	0.984
$\delta^{15}N$	0.07	0.701	0.34	0.053	0.16	0.390	-0.07	0.700	-0.1	0.573

Figures

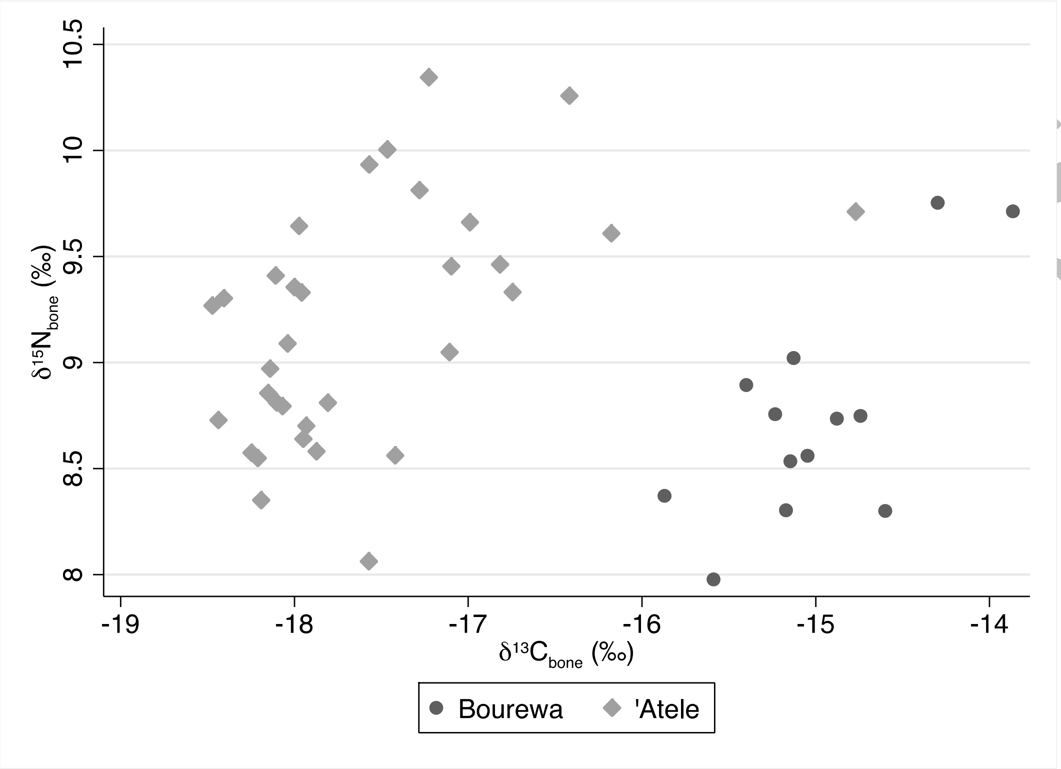

Figure 2. δ^{13}C and δ^{15}N bone collagen isotope results for the Bourewa and `Atele remains.

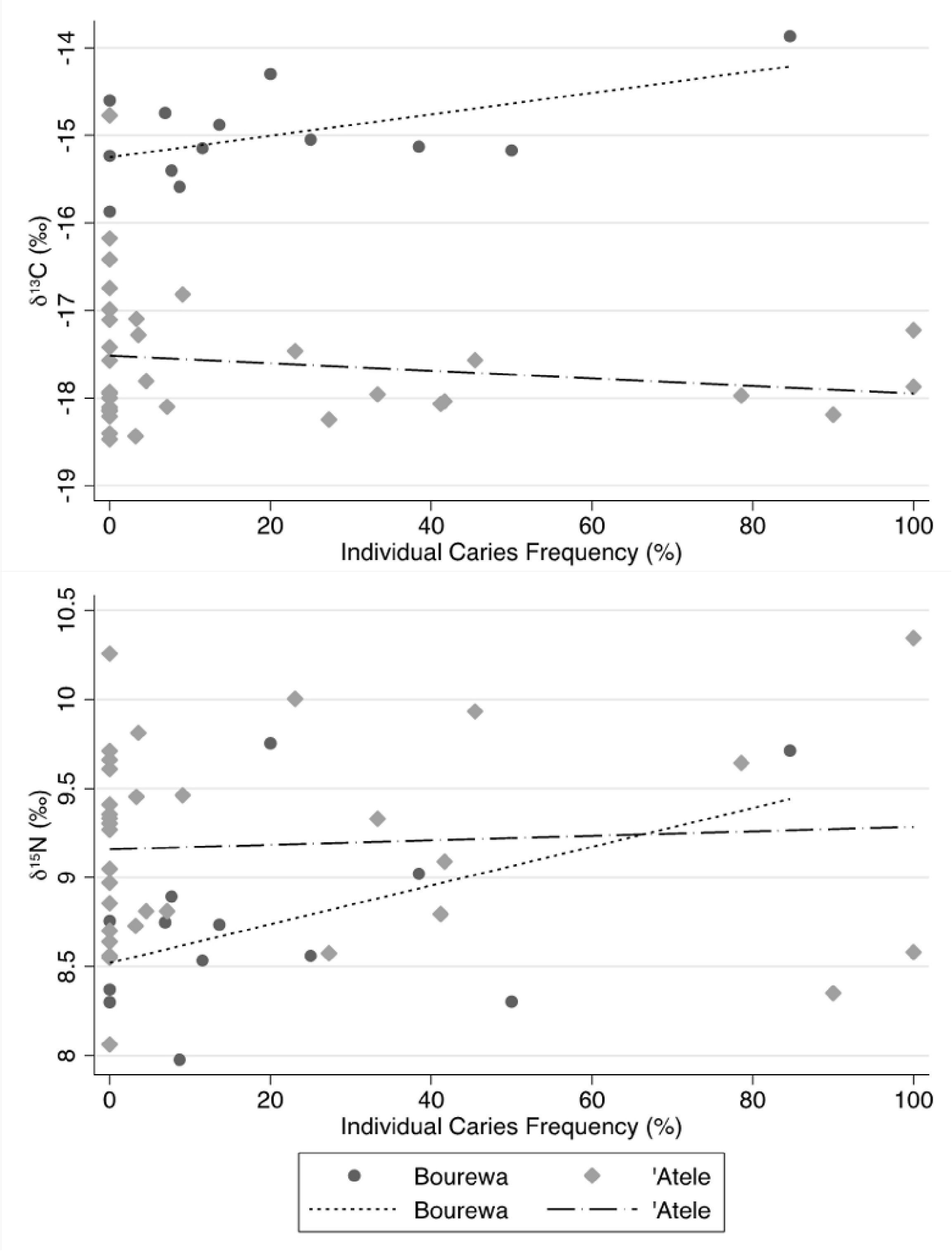

Figure 3. $\delta^{13}C$ and $\delta^{15}N$ plotted against individual caries frequency by site with linear regression lines.

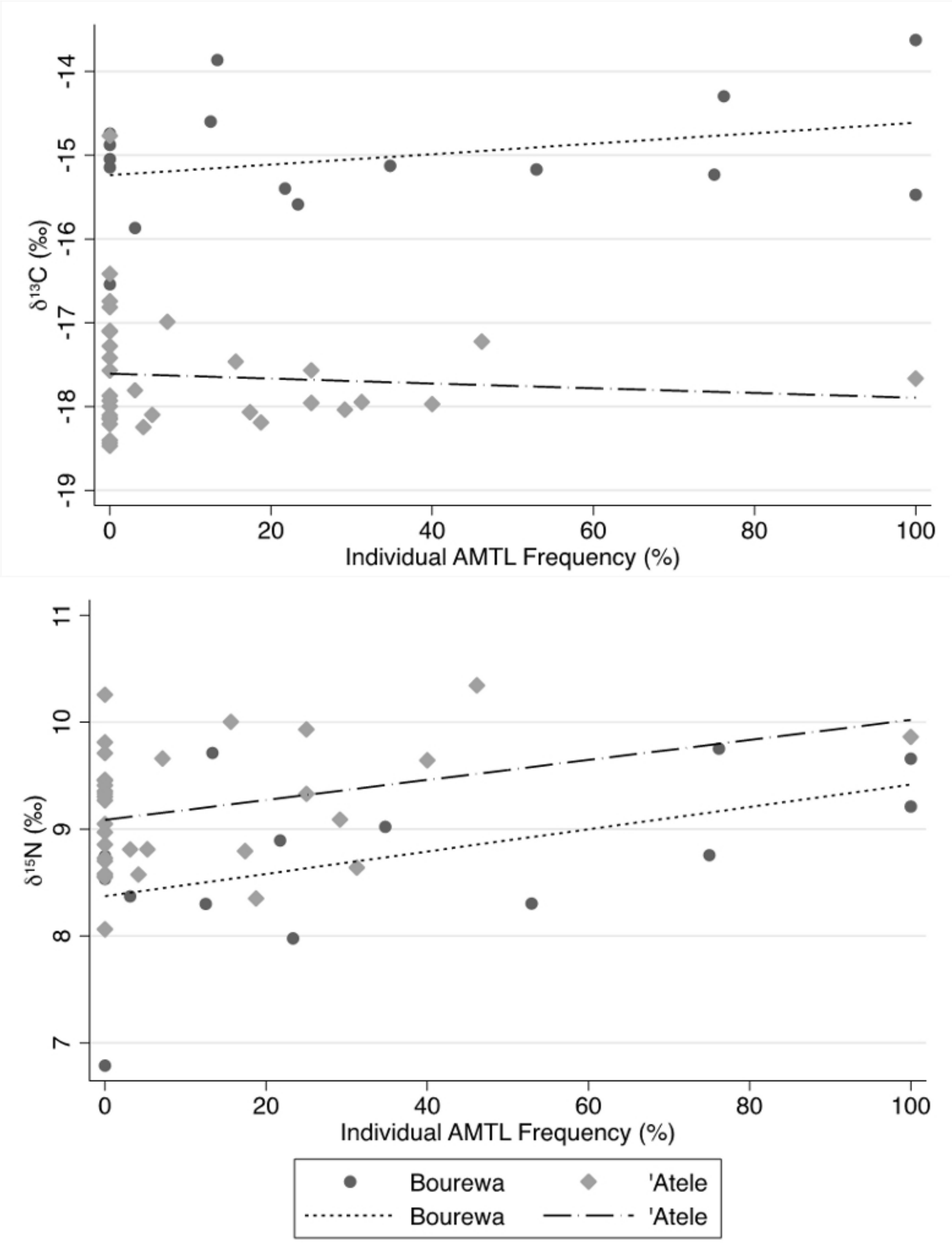

Figure 4. $\delta^{13}C$ and $\delta^{15}N$ plotted against individual AMTL frequency by site with linear regression lines.

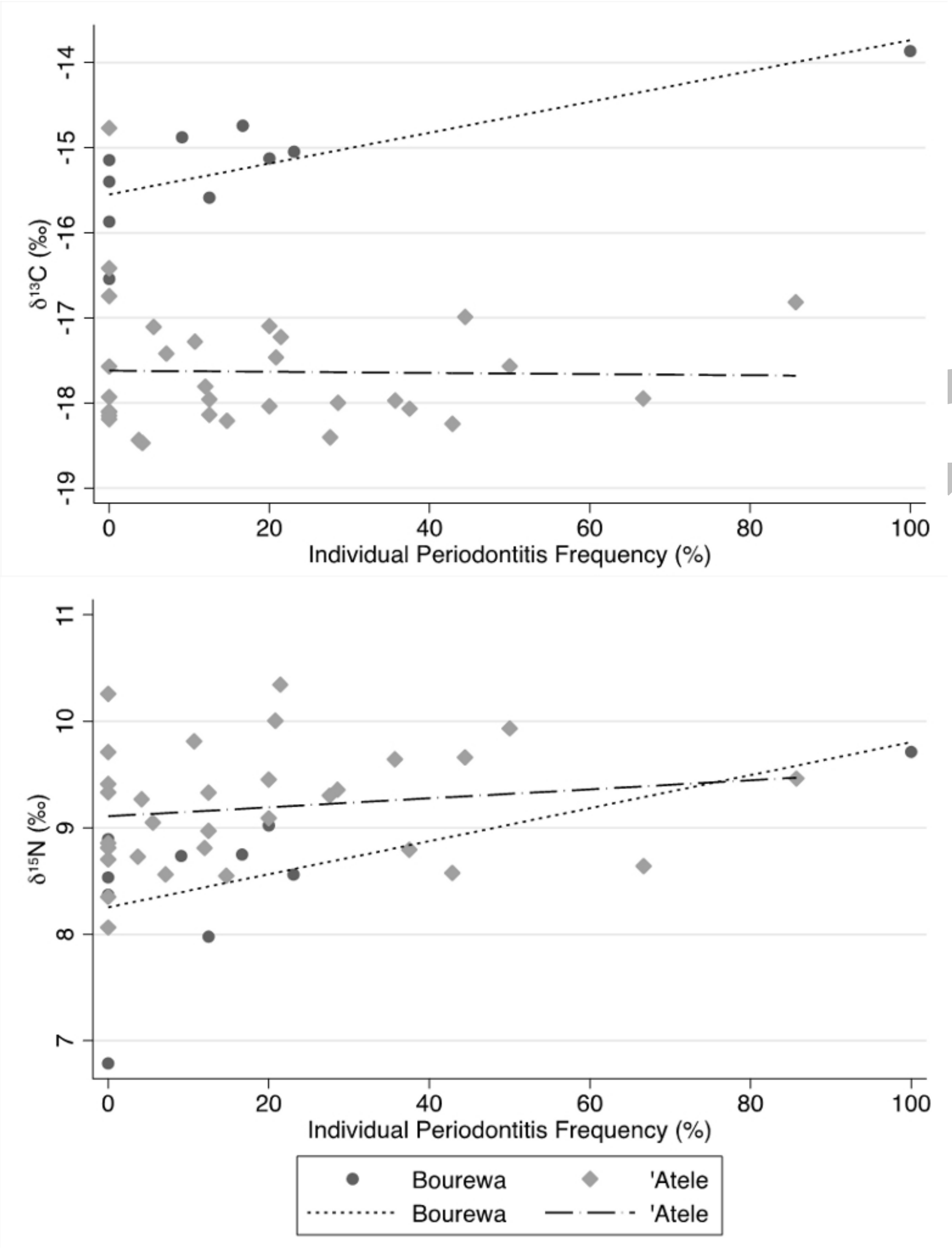

Figure 5. δ^{13}C and δ^{15}N plotted against individual periodontitis frequency by site with linear regression lines.

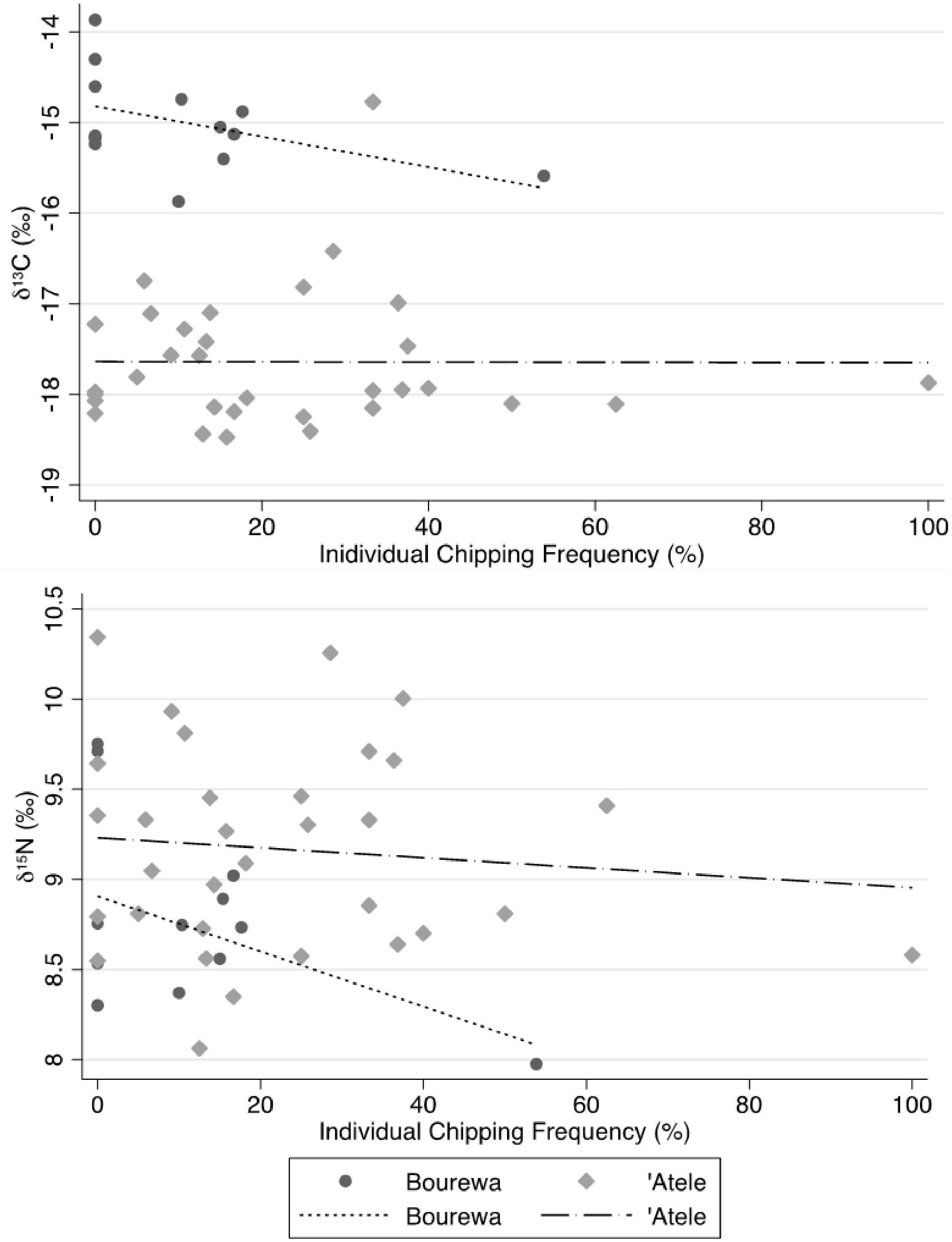

Figure 6. $\delta^{13}C$ and $\delta^{15}N$ plotted against individual occlusal edge chipping frequency by site with linear regression lines.

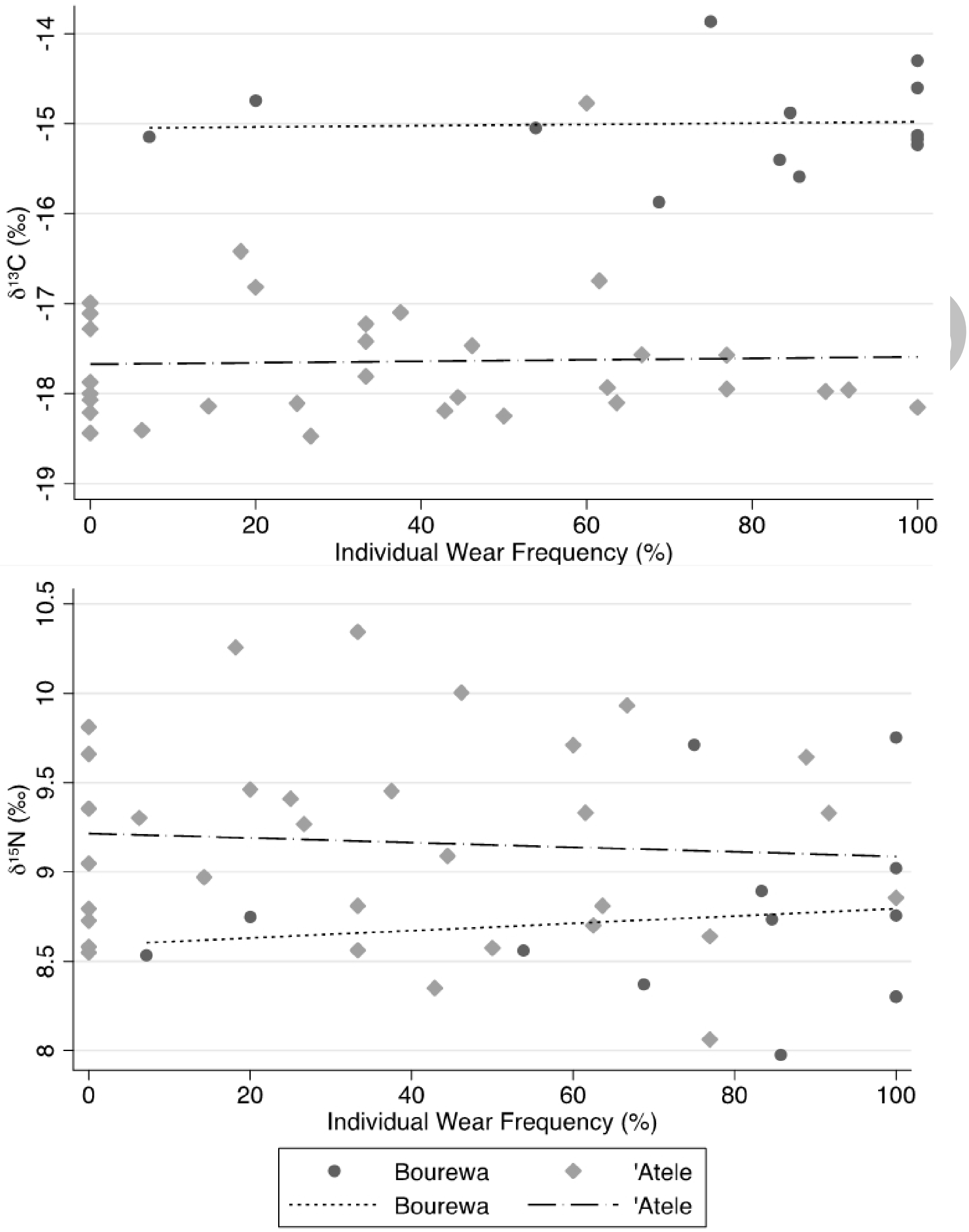

Figure 7. δ^{13}C and δ^{15}N plotted against individual dentin exposure frequency by site with linear regression lines.